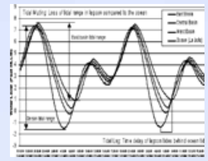
Chapter 2
Physical Evolution



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2.0 PHYSICAL EVOLUTION OF BATIQUITOS LAGOON

Much of the ecological development of Batiquitos Lagoon is derived from the physical evolution of the system. A comprehensive physical monitoring program was to be conducted by the California Department of Fish and Game (CDFG) as provided for in the Draft Land Management Plan for Batiquitos Lagoon Ecological Reserve initially prepared by the lagoon design engineers, Moffatt & Nichol (M&N), and subsequently revised by CDFG (CDFG 1997); however, it was not implemented. As a result, only intermittent physical data were collected during the course of the 10-year biological monitoring program. Most of the data were collected on a limited, opportunistic basis in the first few years following the restoration in order to better interpret the observed biological changes rapidly occurring within the lagoon.

Recognizing the need to, at a minimum, document the current physical conditions in the lagoon, the City of Carlsbad (City) provided funding in 2008 through its Agricultural Conversion Mitigation Fee Grant program to the Batiquitos Lagoon Foundation (BLF) to conduct a one-time assessment of the bathymetric and tidal status of the lagoon. Merkel & Associates (M&A) conducted the investigation, and the collected data have been provided by BLF for use in the present report. In addition, CDFG contracted with M&A to complete hydroprobing of lagoon flood shoal deposits in order to determine the depth of sand accumulation in the west and central basins of the lagoon in preparation for a future rehabilitation dredging effort. These data sets provide additional limited information regarding the physical state of the lagoon.

The lack of regular physical monitoring coincident with the biological data collection has hindered the capacity to fully interpret and understand the evolution of the restored lagoon. Through review of the various intermittent data sets, however, a rough interpretation of physical development of the system has been prepared and discussed below. The considerable temporal gaps, however, create uncertainty as to whether system change has been due to chronic or acute processes. In addition, intermittent maintenance dredging events have influenced the system in a manner that confounds efforts to quantify rates of change between random physical data collection efforts.

It should further be noted that much of the physical data collection has been completed as disjunct and unrelated efforts with differing objectives. As a result, the interpretive use of these data is inherently limited. Much of the data can be characterized as incomplete snapshots of the system, from which this chapter attempts to fill in missing details based on qualitative observations and interpolation. For early system evolution, there is no way to recover the absence of physical monitoring data to further facilitate understanding of the lagoon development. However, for future system evolution, more detailed physical data collection and improved sampling frequency would enhance the overall understanding of physical lagoon function and relationships of the physical condition of the lagoon to the biological condition.

2.1 METHODS

The primary data available to assess the physical development of the lagoon post-restoration are tide data, lagoon elevation data (bathymetry), and aerial photography. The data sources reviewed, and the techniques used to interpret them, are described below.

2.1.1 Tidal Assessment

Tide data were reviewed from three sources: a 1997 post-restoration tidal inlet study (M&N 1997b), tide data collected in July 1998, January 1999, and January 2000 (M&A 2002), and the 2008 physical assessment report prepared for BLF (M&A 2009a).

Specific data collection methods are detailed in each of the reports cited above. In general, tide gauges were deployed within the three lagoon basins, logging water level data continuously. The 1997 study was conducted for a 33-day period and the 2008 study for a 96-day period, while the 1998, 1999, and 2000 data were collected over shorter periods of time.

In both the 1997 and 2008 tidal investigations, the tide loggers were placed well away from the high flow regions of the system, such as at bridges where hydraulic gradients may provide uniquely localized water surface elevations. The loggers were deployed at the southern ends of the west basin and central basin. In the 1997 survey, the east basin logger was placed in the central portion of the dredged basin, approximately 400 feet west of the westernmost edge of the E-2 nesting site. In 2008, the east basin logger was placed approximately 2,300 feet further west in a location that ensured the logger would not ever be exposed during low tides. Shallowing of the eastern portion of the basin, including the location of the 1997 tide monitoring station, made it unclear if this area would be exposed at the lowest tides of the study period. For both studies, the collected lagoon tide data were compared to ocean tide data retrieved from the nearest tidal station, located 15.5 miles south of Batiquitos Lagoon, in La Jolla at Scripps Pier (NOAA Station 9410230).

The findings of the 2008 study are presented below and compared where appropriate to the 1997 study, though the short duration and seasonal timing of the 1997 data collection limit the usefulness of direct comparisons. The less comprehensive 1998 through 2000 data from the interim years were used when applicable to look at conditions between the 1997 and 2008 studies. Analyses of the 2008 data included comparisons of lagoon and ocean tides to determine the time lag and tidal muting within the lagoon. Scatter plots were generated to calculate an equation by which the loss of lower low tides and the tidal lag could be currently predicted for each basin of the lagoon. All vertical data are presented in feet Mean Lower Low Water (MLLW).

2.1.2 Bathymetric Assessment

Four sets of bathymetric data were reviewed. The sources of these data sets and methods of development are as follows:

<u>1996 As-built Bathymetry</u>

A post-dredging bathymetric survey at +5 feet MLLW and below was completed in multiple phases from 1994 through 1996 by MK Centennial, the project construction manager. Survey data above +5 feet MLLW were based on a 1990 land survey by Melchior Land Surveyor, Inc. Survey data were compiled on a single final as-built drawing dated February 13, 1997 by M&N. This composite survey constituted the record drawings for the lagoon enhancement project.

<u>1999 Bathymetry</u>
In February 1999, M&A, with Noble Consultants, collected bathymetric data throughout the lagoon. This survey was conducted as an unfunded adjunct to the biological monitoring program and provided the first post-construction review of the site following the composite 1996 as-built survey.

<u>2000-2001 Bathymetry</u>
In October 2000, Noble Consultants collected bathymetric data in the east basin. This survey was augmented in January and February 2001 with surveys of the central and west basins, respectively. Because the central and west basin surveys occurred during periods of maintenance dredging, areas near the flood shoal were in a state of flux during this survey. The surveys, however, provide a good intermediate "snapshot" of conditions in the lagoon approximately five years post-restoration.

<u>2008 Bathymetry</u>
As part of the 2008 physical assessment report prepared for BLF, M&A collected bathymetric data in the three lagoon basins in July 2008 (M&A 2009a). These data are the most comprehensive and current and were therefore the focus of the overall analysis presented below.

<u>Data Analysis</u>
For all data sets, the point data were used to create a Triangular Irregular Network (TIN) surface. The TIN surface was converted into a grid with a cell size of 1 m^2, and the grid was used to create bathymetric contours. The surface conditions were interpolated to coincident 1-m^2 horizontal grids to facilitate analyses. Spatial analyses of elevation change were accomplished using ESRI ArcGIS, which allows for subtraction of coincident grid cells to calculate elevational and volumetric change by grid cell.

In this manner, changes in bathymetry were determined for the 1996 as-built conditions to 1999, from the as-built conditions to 2008, and from 1999 through 2008. Rates of change were then calculated as annual values by dividing the elevational change measured between bathymetric survey events by the number of years between events. The purpose of this last calculation was to assess whether the system has maintained a relatively steady rate of bathymetric change post-restoration.

<u>Maintenance Dredging Tracking</u>
An important factor to consider when assessing the movement of sediment within the lagoon is its intentional export through dredging. The primary maintenance requirement originally identified in the project design and Draft Land Management Plan for Batiquitos Lagoon Ecological Reserve (CDFG 1997) was the dredging of accumulated beach sand transported into the system. The rapid formation of large flood shoals within the west and central basins clearly confirmed this need. The Draft Land Management Plan had identified the anticipated need to dredge the west basin on a schedule of approximately every three years; the east basin every five to ten years; and the central basin, requiring dredging less often than the east basin, on an "as needed" basis (CDFG 1997).

CDFG has been responsible for lagoon maintenance dredging since the management of the lagoon was given to it following construction. Shoal dredging in the west and central basins has occurred on a recurrent schedule, roughly biennially rather than every three years (west basin) or as-needed (central basin) as predicted by the Draft Management Plan. The east basin has never been dredged, which is less frequent than the need predicted in the Draft Management Plan (every five to ten years).

CDFG Batiquitos Lagoon Ecological Reserve Manager, Tim Dillingham, has tracked maintenance dredging efforts at the lagoon over time, with flood shoal sands in the western and central basins dredged and placed back on the coastal beaches or used to replenish sandy substrate on nesting sites within the lagoon. Data regarding maintenance dredging activities were provided from CDFG to further the present volumetric and interpretive analysis of bathymetric changes within the lagoon.

<u>Flood Shoal Hydroprobing</u>
In preparation for future maintenance dredging activities, CDFG contracted M&A to conduct a very limited subsurface sampling program in the central and west basin to determine the thickness of sand deposits potentially suited to dredging removal and beach replenishment. This program was undertaken to provide a preliminary estimate of sand volumes that may be present and exportable in a more extensive rehabilitation dredging effort that exceeds the scale of the historic maintenance dredging activities conducted in the lagoon. Hydroprobing was performed using a water jet corer with a fluidized material recovery tube that brought the material to the surface for inspection and field characterization. The sampled stations were characterized by strata based on overall texture, color, odor, cohesion qualities, and effort required to advance or extract the probe (M&A 2009b). Several of the probing locations were selected as areas of particular interest in the central basin to evaluate extent of sand shoaling and subsidence within the sand-capped fine sediment disposal pit in the central basin. The findings from this effort were used, along with the bathymetric change assessment, to make a rough estimation of the amount of subsidence that occurred in the sediment disposal pit in the central basin.

2.1.3 Hydrogeomorphic Evolution
Additional tools used to assess post-restoration physical changes within the lagoon included high-resolution, geo-rectified aerial photographs that were used to map vegetation, but also provided a record of visible physical changes to lagoon morphology over time. For purposes of tracking physical change in the lagoon, photos from 1997, 1998, 2001, 2003, 2005, and 2006 were examined to investigate the forces acting on various areas, the likely process of change, and the ramifications for future system development. Other information considered included extensive field observations of sediment erosion and deposition patterns, as well as sediment grain size analysis data collected in concert with benthic and vegetation investigations.

2.2 RESULTS

2.2.1 Tidal Assessment
Figure 2-1 is a two-day excerpt from the 2008 tidal monitoring data set, shown as an example of the collected data. Two of the factors examined in the tidal assessment were tidal muting and

tidal lag in the lagoon. The first measures the loss of tidal range (the vertical change in elevation between the high and low tides) when comparing the lagoon basin tides to the ocean tides (Figure 2-1). The second assesses the tidal lag between the ocean and each of the basins, which is the amount of time it takes the basin tides to reach a given tide stage (lower low tide in the Figure 2-1 example) in comparison to the ocean. The relevance of these factors will be discussed in the following Discussion section.

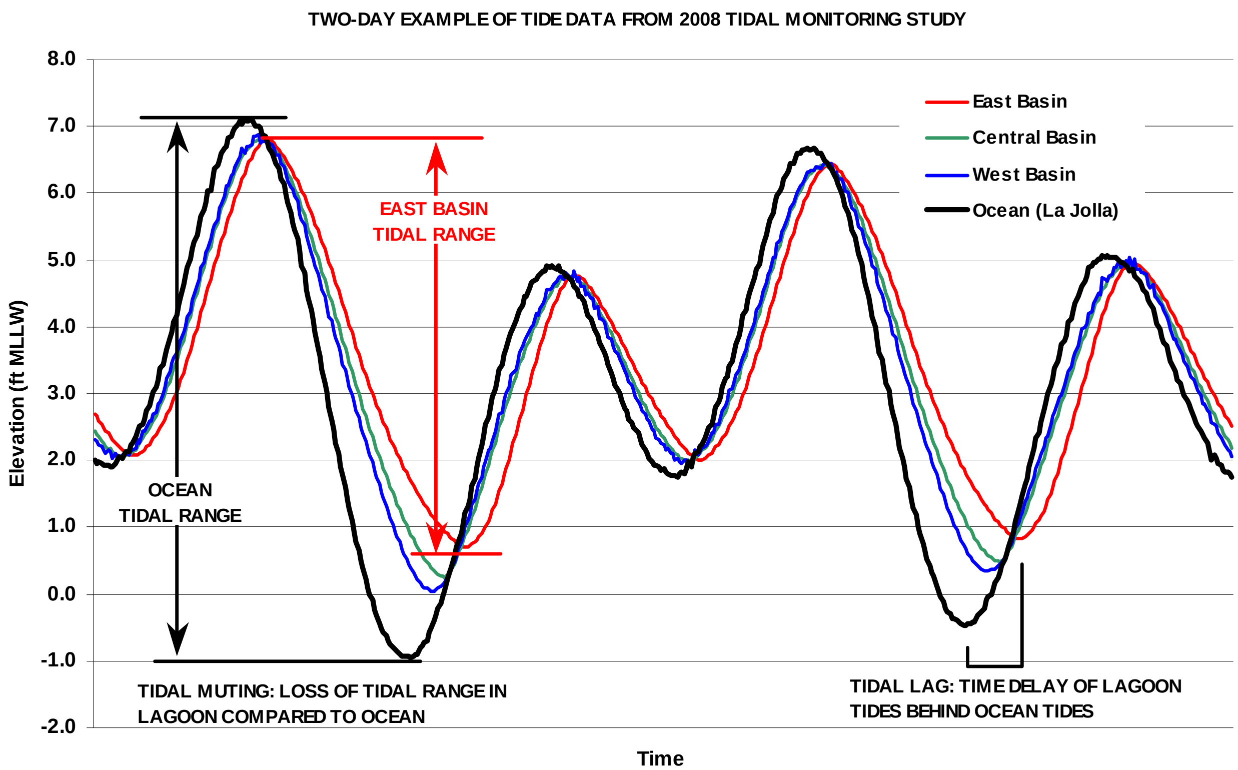


Figure 2-1. Example of tidal muting and tidal lag on plotted tides.

Comparison of the 1997 and 2008 tidal data revealed that the overall pattern of the tidal curves was the same immediately after the restoration as it is today. The lagoon high tides generally reached or were near the ocean high tides, and the lagoon low tides did not fall as low as the ocean low tides. The principal determinants of the tidal condition in the lagoon are the ability of water to fill the lagoon as the ocean tide rises and then its ability to drain as the ocean tide falls within the time period of an ocean tide cycle.

Constraints on tidal exchange include the inlet dimensions, nearshore bathymetry across the inlet mouth, constriction points at the railroad bridge and the Interstate 5 (I-5) bridge, and the accreted sand shoals in the west and central basins. While the hardened dimensions of the inlet and bridge crossing have remained constant due to placement of armor stone sills beneath the bridge structures, the dynamic lagoon shoaling exerts considerable control over the tidal regime within the lagoon basins and is the major factor that can be controlled through management actions.

The effects of constrictions on tidal exchange are most significant under low tidal amplitudes and ebbing (falling) tides. As the ocean tide drops, creating a gradient between the ocean and lagoon, the surface water is initially able to exit the lagoon relatively unrestricted. As the lagoon becomes shallower, however, the water experiences a reduction in the differential head between the lagoon and the ocean, diminishing cross-sectional area through constricted channels and an increased effect of bed friction within the channels. Forcing the ebbing water through a smaller area impedes its flow to such a degree that the lagoon cannot fully drain out before the ocean tide has already reached its low and begun to rise again. In Figure 2-1, these effects can be seen as impaired drainage curves, with the lagoon tide departing from the ocean tide's sinusoidal curve and the truncation of the lagoon range and shallowing of its slope in comparison to the ocean tide curves. Tidal impairment of this sort is greatest during periods of high rates of water exchange during spring tide periods when the lowest and highest tides are achieved.

On the incoming tide, physical constraints on tidal exchange are less relevant. As the tide rises, the widening of the effective flow areas and the increasing water depth both rapidly increase cross-sectional flow area and reduce the relevance of bed friction. Further, tidal flow is enhanced by wave propagation into the inlet from ocean swell.

Tidal Muting

Table 2-1 presents the mean tidal elevations in the lagoon and ocean during the 2008 study (July 2 to October 6, 2008). The elevations indicated are defined as:

Mean Higher High Water	= Average of higher high daily tides
Mean High Water	= Average of all high tides
Mean Sea Level	= Average of all recorded water levels
Mean Low Water	= Average of all low tides
Mean Lower Low Water	= Average of lower low daily tides
Highest water level	= Maximum water level during monitoring period
Lowest water level	= Minimum water level during monitoring period

All definitions above are based on the measured tides during the study period and as a result do not reflect the long-term averages represented by tidal epochs used to establish a tidally based datum (*e.g.*, MLLW for the 1983-2001 tidal epoch).

Table 2-1. Tidal elevations in Batiquitos Lagoon and the ocean (La Jolla) - July 2 to October 6, 2008.

Elevations (feet MLLW)	Ocean	West Basin	Central Basin	East Basin
Mean Higher High Water	5.7	6.0	6.0	5.9
Mean High Water	5.0	5.2	5.2	5.1
Mean Sea Level	3.2	3.5	3.6	3.5
Mean Low Water	1.3	1.8	1.9	2.0
Mean Lower Low Water	0.4	1.1	1.2	1.4
Lowest water level	-1.5	0.0	0.3	0.7
Highest water level	7.4	7.5	7.4	7.4

In the 2008 study, the mean lower low water was approximately 1.0 foot higher in the east basin than in the ocean. Although the lowest ocean tide during the monitoring period was –1.5 feet MLLW, the east basin never dropped below +0.7 foot MLLW.

Table 2-2 presents the tidal ranges for the ocean, west, central, and east basins of the lagoon during the 2008 study. The ranges are presented for the maximum range achieved, as well as for average daily highs and lows (MLLW to MHHW range) and the average of all high and all low tides (MLW to MHW range). The maximum muting, or loss of tidal range in comparison to the ocean, in the west, central, and east basins was 1.4 feet, 1.7 feet, and 2.2 feet, respectively. As seen in Table 2-1, the loss of range is almost exclusively due to loss of lagoon drainage at the lowest tides.

Table 2-2. Tidal ranges in Batiquitos Lagoon and the ocean (La Jolla) - July 2 to October 6, 2008.

Elevations (feet)	Ocean	West Basin	Central Basin	East Basin
Maximum tidal range	8.9	7.5	7.2	6.7
MLLW to MHHW range	5.3	4.9	4.8	4.5
MLW to MHW range	3.7	3.4	3.3	3.1

Figure 2-2 plots the lowest daily tide in each of the three lagoon basins against the lowest daily ocean tide in the 2008 study. The ocean tide is plotted in black to illustrate the deviation of the basin tides from the ocean. The equation describing each regression line is included. The loss of low tides increased from the west to east basin and was most pronounced during spring ocean tides (around full and new moon periods).

The 1997 tide condition immediately following the restoration completion was examined over a 33-day period from February 11 to March 22, 1997 (M&N 1997a), while the 2008 investigation was conducted for a 96-day period from July 2 through October 6, 2008 (M&A 2009a). Because the oceanic tidal range and shape of the tidal harmonics differ by season as well as oceanic and atmospheric conditions, direct comparisons between short duration survey results are not possible. However, by examining various aspects of the tidal monitoring data from 1997 and 2008, it is possible to detect and characterize some large-scale changes, although subtle differences may likely be attributable to variability between studies and the sampled tidal periods.

A certain degree of tidal muting was anticipated in the restoration modeling and design. This muting was documented in the 1997 M&N post-restoration tidal monitoring study. The muting has been exacerbated over time, and by 2008, considerable additional muting was observed over that detected in 1997. There was essentially no change in the high tide conditions in the lagoon between 1997 and 2008. Looking at the mean lower low water conditions in 1997, they were reported to be the same in each basin and roughly 0.7 foot above the reported ocean mean of 0.0 feet MLLW for that time period. In 2008, however, there was a distinct gradient of increased muting from west to east, with the east basin 1.0 foot above the ocean mean lower low water elevation for the monitoring period (Table 2-1). During the 1997 study period, the ocean tide did

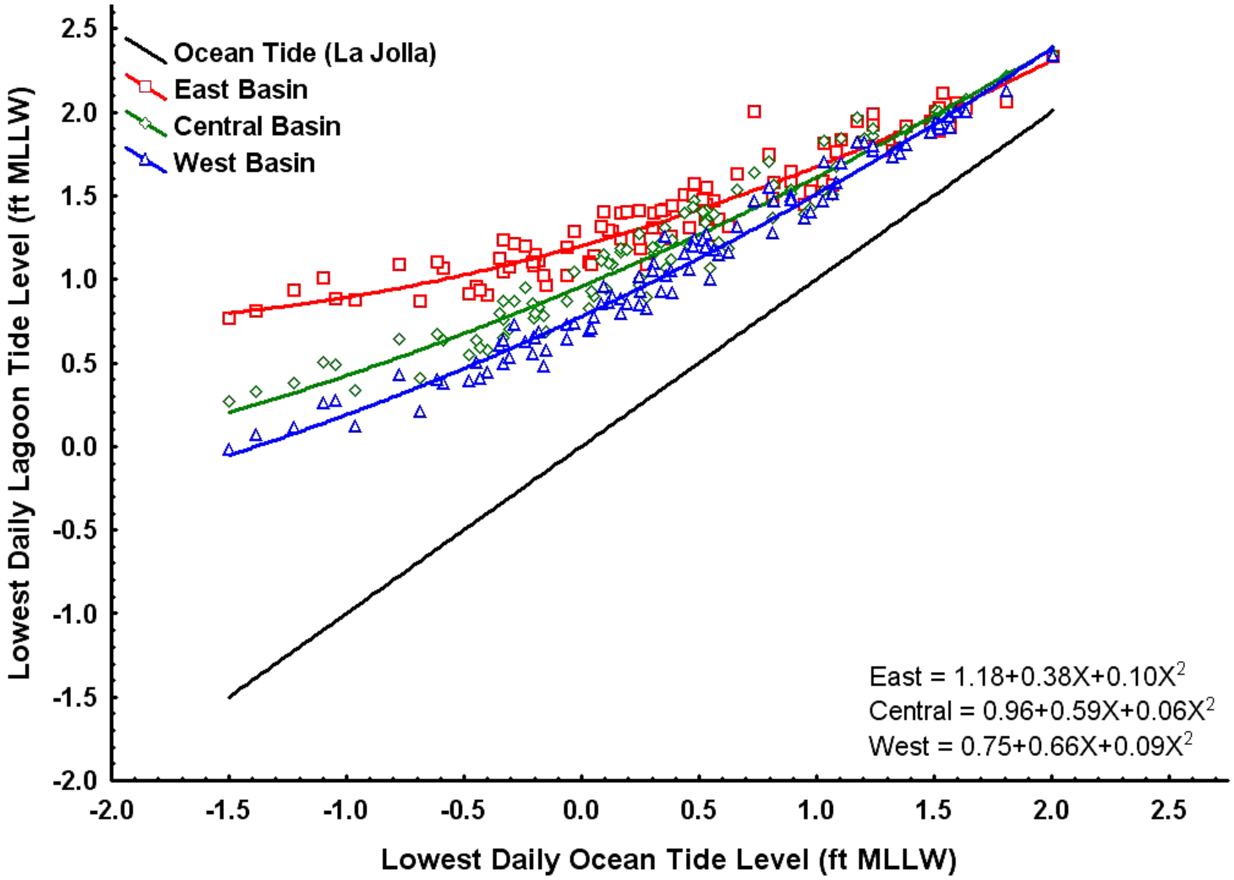


Figure 2-2. Lowest daily low tides in the Batiquitos Lagoon basins plotted against the lowest daily ocean tides (July 2 to October 6, 2008).

not fall below –1.0 foot MLLW, but all three lagoon basins were able to drain as low at 0.0 feet MLLW. Using the equations presented in Figure 2-2, at a –1.0 foot MLLW ocean tide in 2008, the east basin would have drained down only to +0.9 foot MLLW.

During the 1997 study (M&N 1997a), the maximum tidal range in the east basin was approximately 82% of the ocean range, while in the 2008 study, the east basin range was approximately 75% of the ocean range during that period. Because the 2008 investigation looked at a period of time with more extreme tidal ranges, the deviation between 1997 and 2008 is even greater than suggested by the disparity expressed by these percentages. For the mean tidal range (MHW to MLW), the variance between 1997 and 2008 is diminished from that observed in the extreme tidal exchange. The percentage of the mean ocean tidal range exhibited in the east basin was 92% in 1997 and 84% in 2008.

The 1999 and 2000 data sets were not large enough to make comparisons of tidal amplitudes and ranges with the 1997 and 2008 conditions.

Tidal Phase Lag

Figure 2-3 presents the 2008 tidal phase lag between the ocean reaching the lowest tide of the day and the lagoon basins reaching the lowest tide of the day, including equations for the regression lines in each basin. The time lag increased from west to east and was most pronounced during low spring tides (around full and new moon periods). At the lowest ocean tides, the maximum lag in the west, central, and east basins was 96, 120, and 186 minutes, respectively.

The 1997 post-restoration tidal monitoring study (M&N 1997a) found the greatest low tide lag in the west basin during the monitoring period to be 15 minutes behind the ocean tide and the greatest in the east basin to be 45 minutes behind the ocean. Because this monitoring period did not include the broader tidal ranges experienced in 2008, the maximum tidal lags reported in 1997 would naturally be less than would have been detected had the study been conducted over a period capturing a greater oceanic tide range.

Reviewing the interim data collected in January 1999 over a short spring tide period, the maximum low tide phase lag in the west, central, and east basins was 55, 120, and 125 minutes, respectively (calculated to the closest 5-minute interval). Over a short spring tide period in January 2000, the maximum lag in the west and east basins was 100 and 120 minutes, respectively (calculated to the closest 20-minute interval).

While the magnitude of low tide lag in the lagoon has clearly increased over time, the absolute phase lag increase cannot be determined due to differential monitoring periods and lack of available raw data sets for the 1997 monitoring period. As with tidal amplitude muting, the tidal period under which monitoring was conducted plays a strong role in defining the extent of tidal lag experienced within the system. The 1997 and 2008 data were not collected during directly comparable time periods.

Periodic dredging to remove portions of the flood shoals in the west and central basins (1999, 2000, 2001, 2002, and 2003) likely resulted in a temporary reduction of tidal muting and lag at that time. However, the phase lag and low tide muting within the system remain significant.

The high tide lag was not examined in this analysis. High tide lags within systems that exhibit low tide muting are generally much less pronounced due to increased sectional area and reduced bed friction as the tide rises. Figure 2-1 exhibits this characteristic very well, while Figure 2-3 illustrates the reduced lag with higher elevations of the low tide.

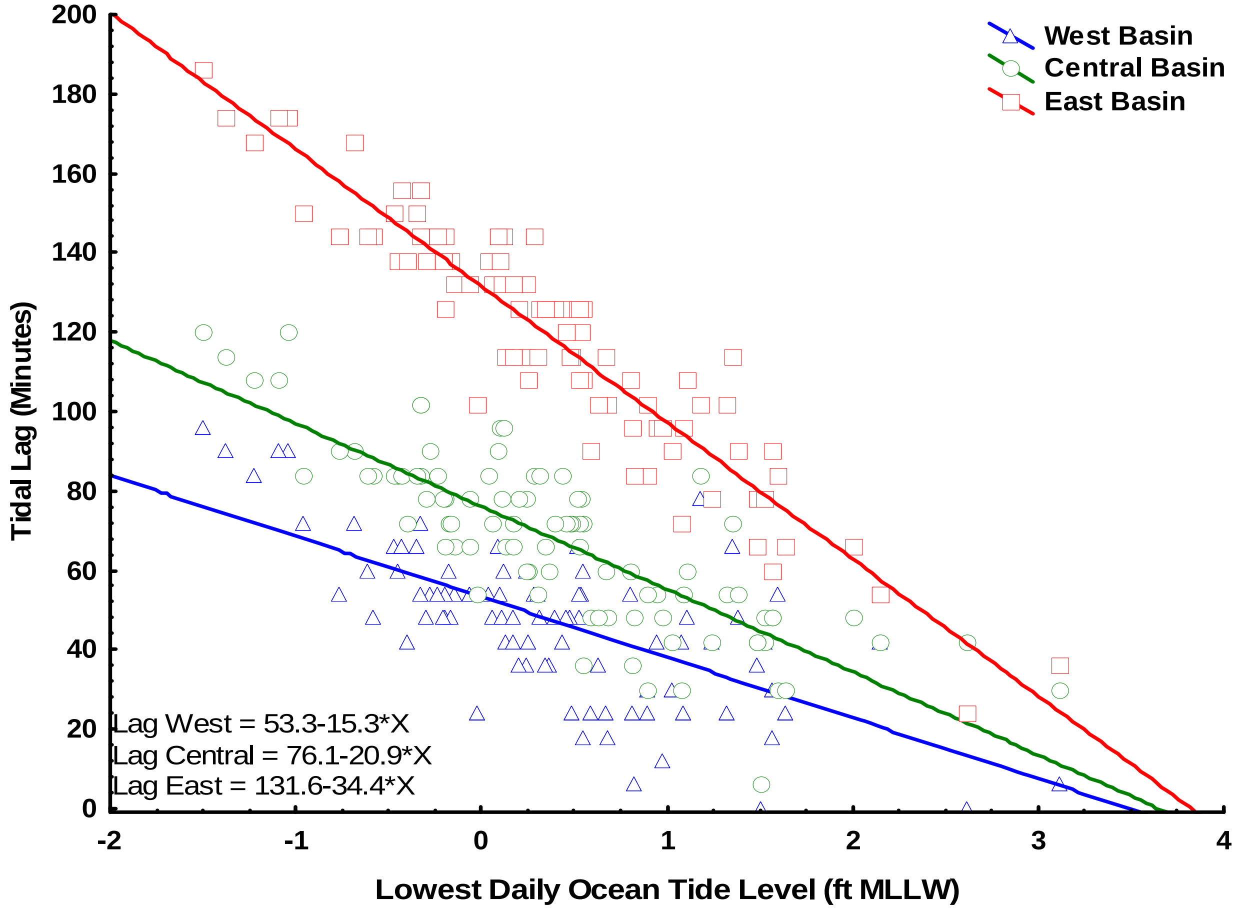
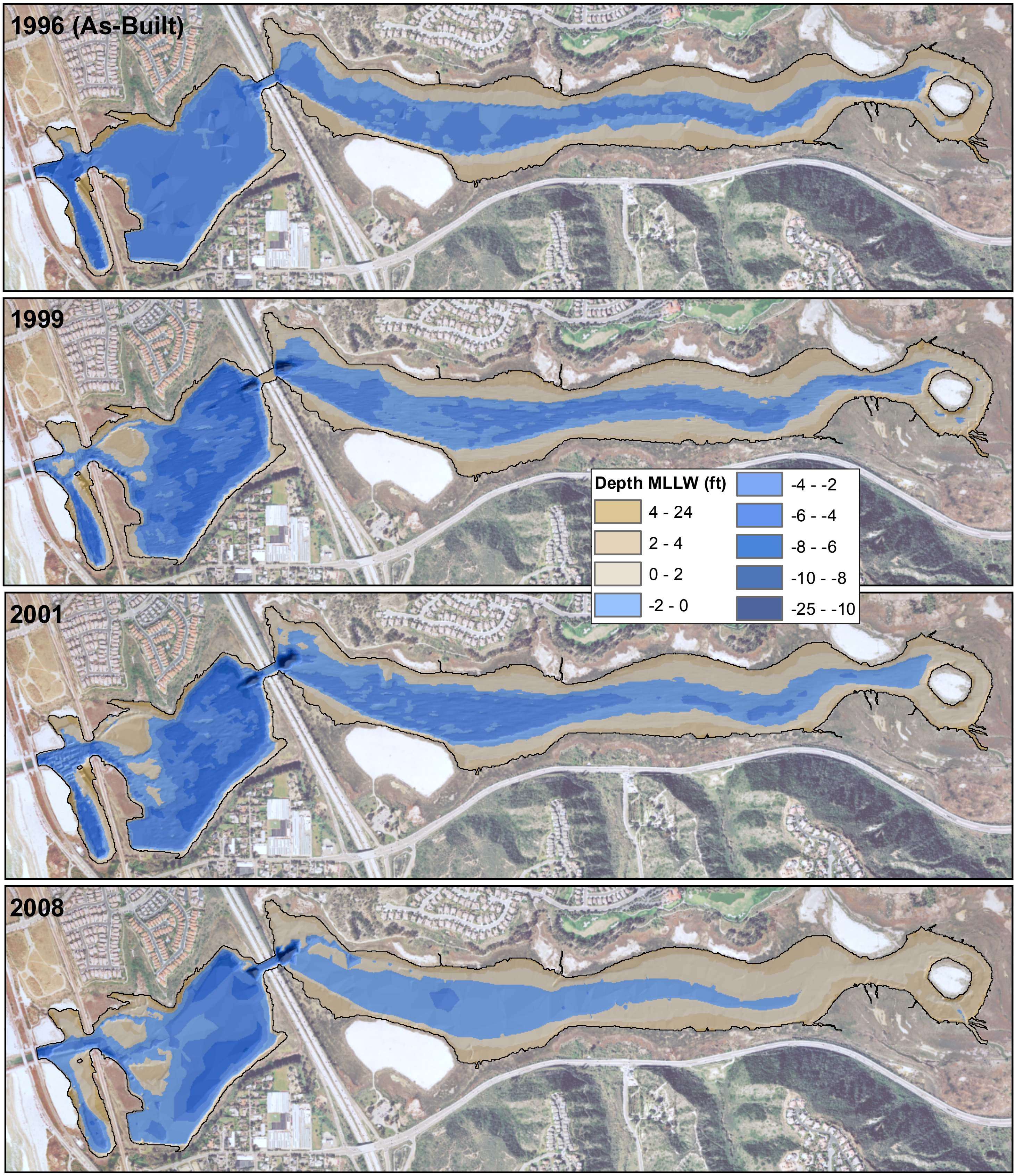


Figure 2-3. Tidal lag (minutes) in the Batiquitos Lagoon basins plotted against the lowest daily ocean tides (July 2 to October 6, 2008)

2.2.2 Bathymetric Assessment

Bathymetry

The results of the 1996 (as-built), 1999, 2001, and 2008 bathymetric surveys have been standardized to a coincident survey area and plotted as color bathymetric charts (Figure 2-4). By comparing the sequential surveys, it is possible to visualize the areas and quantify volumes of sediment gains and losses through time (Figure 2-5). The individual interval surface comparisons, however, provide only snapshots of the evolution of the lagoon without a context of directional evolution from the baseline condition (1996 as-built). For this reason, comparisons between each post-construction survey and the 1996 as-built condition were also made, including a final subtractive analysis (2008 minus 1996 as-built) to document the cumulative changes in bathymetry over the 12-year post-opening history of the lagoon (Figure 2-6). The net volumetric changes presented in these figures was calculated by subtracting the bathymetric surfaces and are presented by lagoon basin in Table 2-3.



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Bathymetric conditions
1996, 1999, 2001, & 2008

Figure 2-4

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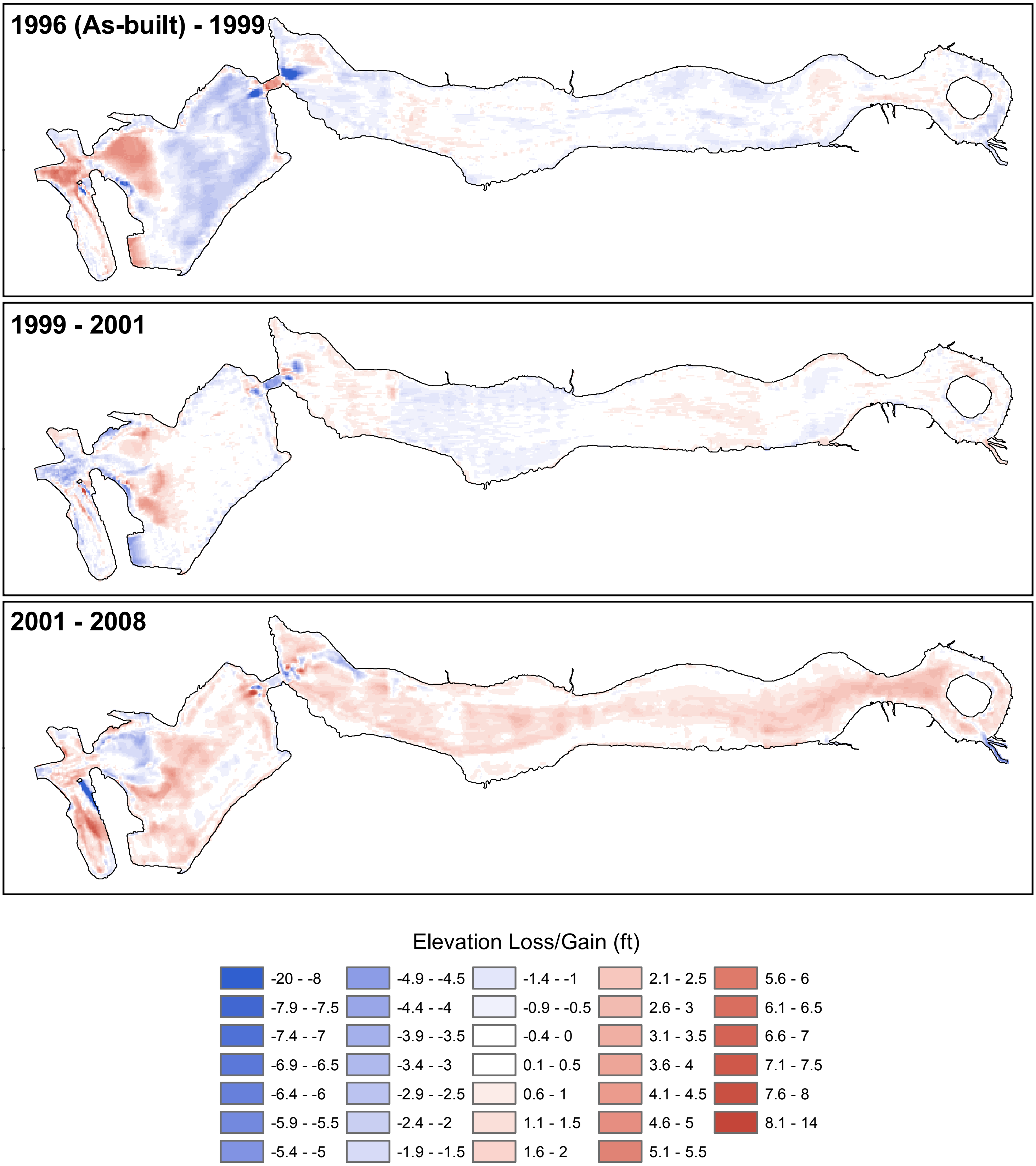

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Survey to survey elevational change analysis

Figure 2-5

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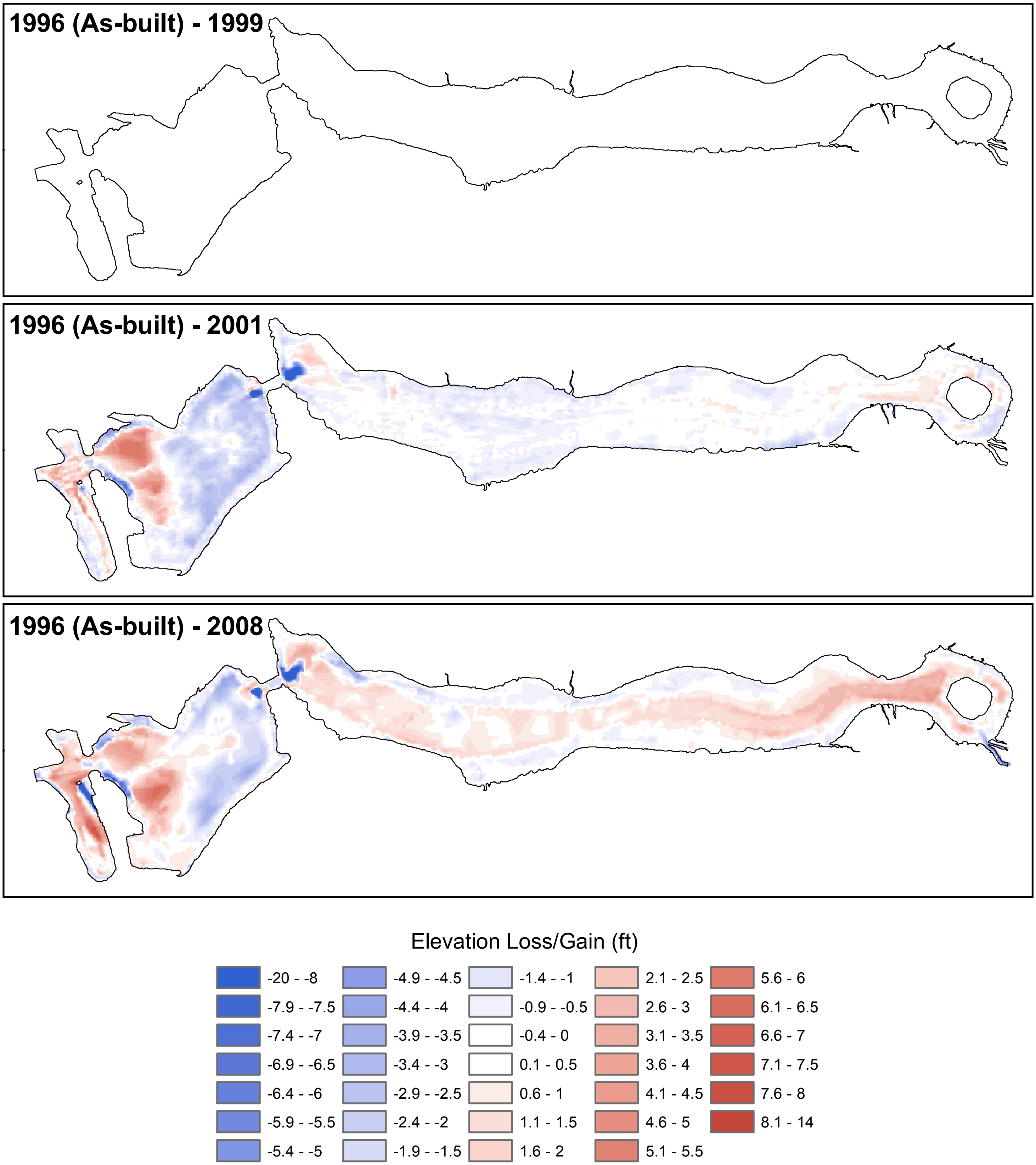

N W E S

Survey to as-built elevational change analysis

Figure 2-6

Merkel & Associates, Inc.

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Table 2-3. Volumetric changes in bathymetric surface from as-built (1996) to 2008.

Survey	West Basin		Central Basin		East Basin		Total Lagoon		
Interval	Gain	Loss	Gain	Loss	Gain	Loss	Gain	Loss	Net
Sediment Volume Change - Survey Interval to As-Built (yd^3)									
1996 to 1999	34,746	(9,555)	62,772	(151,706)	41,327	(131,700)	138,845	(292,961)	(154,116)
1996 to 2001	21,080	(10,594)	71,165	(161,352)	32,447	(140,311)	124,693	(312,257)	(187,564)
1996 to 2008	47,969	(18,641)	92,876	(112,568)	206,311	(75,682)	347,155	(206,891)	140,264
Sediment Volume Change - Survey Interval to Survey Interval (yd^3)									
1996 to 1999	34,746	(9,555)	62,772	(151,706)	41,327	(131,700)	138,845	(292,961)	(154,116)
1999 to 2001	8,696	(23,397)	47,910	(49,123)	67,347	(84,807)	123,954	(157,328)	(33,374)
2001 to 2008	37,342	(18,500)	106,546	(36,052)	264,146	(25,580)	408,033	(80,131)	327,902

The survey-to-survey bathymetric change data were then standardized as annualized rates of volumetric change (Table 2-4). These volumetric comparisons only account for net changes in bathymetry and do not account for materials that have either been exported (naturally or by dredging) from the system between bathymetric surveys or intrinsically changed volume, such as lagoon floor subsidence or through surface sediment consolidation.

Table 2-4. Annualized rate of volumetric change based on bathymetric surface comparisons

Survey	West Basin		Central Basin		East Basin		Total Lagoon		
Interval	Gain	Loss	Gain	Loss	Gain	Loss	Gain	Loss	Net
Annualized Rate of Change - Survey Interval to Survey Interval (yd^3/yr)									
1996 to 1999	17,373	(4,777)	31,386	(75,853)	20,664	(65,850)	69,423	(146,480)	(77,058)
1999 to 2001	2,899	(7,799)	15,970	(16,374)	22,449	(28,269)	41,318	(52,443)	(11,125)
2001 to 2008	5,335	(2,643)	15,221	(5,150)	37,735	(3,654)	58,290	(11,447)	46,843

In Figures 2-5 and 2-6, serial plots of the changes in lagoon bathymetry reveal evidence of shoal accumulation, dredging, scouring erosion outside of the armored sills beneath the bridges, erosion and subsequent loss of the abandoned railroad spur in the west basin, and shoreline erosion and deeper channel deposition. However, subtractive surfaces only show net differences between the two surfaces and do not directly account for mechanisms of surface change. There are several causative agents of bathymetric change that are considered below to better explore the sources and fates of sediment within the lagoon. These agents include maintenance dredging, central basin subsidence, and sedimentation.

Maintenance Dredging

Intermittent maintenance dredging of the flood shoal has been conducted to remove accumulated littoral sand and replace it on coastal beaches. To date, CDFG has dredged an estimated 206,838 cubic yards of sand from the west and central basins during multiple dredging events from 1998 through 2007. The dredging conducted has not been evenly distributed over time. Over the first five years (1997-2001), only 50,162 cubic yards of sand was dredged (approximately 10,000 yd^3/yr). From 2001 through 2007 an additional 156,676 cubic yards was dredged (approximately 22,000 yd^3/yr). On average, approximately 85% of this sand has been derived from the central basin and 15% from the west basin. Maintenance dredging history as tracked by CDFG is presented in Table 2-5.

Table 2-5. Maintenance dredging volumes removed from Batiquitos Lagoon (1998–2007)

Year	Volume (cubic yards)	Additional Information
		LAGOON RESTORATION ACTIVITIES
1994 1995 1996 1997	3,700,000	During this period, 1.7 million cubic yards of sand was dredged from the lagoon as part of the restoration project and placed on South Carlsbad State Beach. An additional 2 million cy of material was dredged and placed within the lagoon as tern nesting si
		MAINTENANCE ACTIVITIES
Winter 1998-1999	10,854	Started permitting and contracting but decision to dredge was made in September and took 4 months to complete. Partial dredging done in 22 days in February following granting of permits by Coastal Commission-available to dredge was estimated at 50,000 (Canam Marine)
Winter 1999-2000	4,268	All from Central Basin - add'l volume from partial dredging by earlier dredge in the winter of 1999-2000 (Canam Marine failed to perform)
Winter 2000-2001	35,040	Volume of 35,040 moved in winter of 2000-2001 (Canam Marine)
2001-2003	91,002	3151 cubic yards from Central Basin, remainder from the Western Basin in winter of 2000-2001 (Canam Marine). This dredge cycle was divided into two winters (01/02, 02/03 because of nesting season)
Winter 2006-2007	65,674	Material placed on North Ponto Beach (Canam Marine)
TOTAL	**206,838**	**VOLUME ALL MAINTENANCE DREDGING CYCLES (1998-2007)**

Table provided by T. Dillingham, CDFG, April 2008

Central Basin Disposal Pit Subsidence

A second confounding factor in assessing volumetric change through subtraction of bathymetric surfaces is the presence of a deep disposal pit in the floor of the central basin that was created during the restoration construction. Beach quality sands were excavated from the vast majority of the central basin to create a 38-foot deep pit, with the sand placed on nearby Ponto Beach. The pit was then refilled with approximately 2 million cubic yards of clean fine sediments dredged from the east basin and subsequently capped with an approximately 2-foot layer of clean sand dredged out of the west basin. After placement of the sand cap, the surface elevation design depth across the pit was to be –1.92 feet MLLW (–4.56 feet NGVD) and even with the surrounding bathymetry. The record drawings prepared for the lagoon suggest that the basin cap was constructed within a close margin of error to this design depth. The deep fill of unconsolidated fine sediments was expected to consolidate over time and thus the central basin would deepen. In such cases, the rate and extent of consolidation can vary widely depending upon sediment characteristics, layering, the volumetric ratio of pore water to sediment, and the weight of the sediment itself and any additional surcharge loads placed on top of the sediment. In the case of the central basin pit, it was anticipated to take months to years to fully consolidate under self-weight (the weight of the consolidating material).

This process has not been monitored nor measured. However, surface bathymetry combined with the recent limited exploratory hydroprobing (M&A 2009b) provides an indication of the potential extent of consolidation of the compressible sediments in the disposal pit. By examining the changes in elevation between the 1996 and the 2008 bathymetry along the margins of the disposal pit and outside of the effective tidal flow area of the lagoon, it is possible to approximate the likely extent of self-weight consolidation that has occurred within the borrow site. Within these marginal areas, neither heavy sediment deposition nor erosion has likely occurred and therefore provide the best bathymetric evidence of consolidation rates. Based on the bathymetric surface comparisons at the margins of the pit, it appears that the self-weight consolidation of sediments within the disposal pit has resulted in an estimated 3.7-foot subsidence (10% of the *in situ* fill depth). As a simple surface assessment, this degree of subsidence would translate into an approximate gain of 355,000 cubic yards of lagoon water volume within the restricted footprint of the central basin sediment disposal pit.

Making this calculation at the pit margins does not address differential properties of material placed in the pit in different areas nor the differential surcharge loading of the sediments by variable cap thicknesses and an expanding flood shoal migrating over the cap. The edges of the excavated disposal pit were likely not within the direct footprint of the fine sediment placement and thus may have been filled by flowing sediments moving outward from the discharge point towards the boundaries of the pit. As a result, these margin areas may have been comprised of more fluidized fine sediments with very limited coarse material and high porewater volume. As a result, these areas would have a greater consolidation capacity than areas within the direct sediment placement footprint. If this were the case, the capacity for consolidation would have been greater at the edges of the pit, and the self-weight consolidation estimated based on bathymetric changes in these areas would tend to overestimate the degree of subsidence.

The 2009 hydroprobing conducted in the lagoon provided stratigraphic characterization of 11 widely distributed points over the central basin sediment cap (M&A 2009b). The sampling program revealed the presence of a complicated layering of fine sediments and overlying sands made up of the original sediment cap and the accreting flood shoal. The probing indicated the presence of deep shoal deposits, lifted mud boils, and areas of blended mud and sand strata. When reviewing these data, it is not possible to identify a simple consolidation profile, rather the best interpolated surface generated from the existing data suggested an average consolidation that may have yielded an approximate gain of 130,000 cubic yards of lagoon water volume or an average 2.2-foot subsidence over the disposal pit.

These two estimates taken together suggest there may be a gain of lagoon water volume from 1997 to 2008 within the restricted footprint of the central basin sediment disposal pit of 130,000 to 355,000 cubic yards. The crude approximations and high degree of uncertainty in these values are the result of a very limited dataset. Absent completion of a more extensive subsurface investigation including sub-bottom profiling and a more comprehensive coring of the cap to determine the depth of accumulated depositional sediment and the contact elevation of sand and mud, it is not possible to determine the full extent of shoal sand and fine sediment accumulated in this basin or the extent of consolidation that has been achieved in the sediment disposal pit.

Sedimentation

The net accretion of sediment seen in some areas in Figure 2-5 is derived from multiple sources. The first is littoral sand capture and deposition within the flood shoals in the west and central basins. The second is fluvial and external erosion inputs, principally from San Marcos Creek but also including Encinitas Creek, small local drainages, and bluff erosion. The third source of sedimentation is internal lagoon erosion and sediment redistribution and deposition. This occurs where shorelines are weathered by wave and tidal action and materials settle into deeper portions of the lagoon. Internal erosion also occurs where current velocities are high as a result of flow constrictions. As channels are scoured to wider or deeper conditions, the eroded sediments are entrained and transported to more quiescent areas of the lagoon and deposited.

The final potential cause of sediment elevation gains within the lagoon may involve uplift of compressible sediments as a result of differential loading. Within Batiquitos Lagoon, uplift of substrate would only be possible at the central basin disposal pit. The loading of the west end of this pit by shoal sand would be expected to compress and displace the unconsolidated muds in the pit. This would tend to result in some broad based uplift or localized mud boils adjacent to surcharging sand loads. The recent hydroprobing conducted in 2009 suggests that a portion of what appears to be flood shoal near the central portion of the central basin may in fact be a mud boil. This area is at an elevation well above the initial constructed surface and had no sand cap or sand layer in the collected core. More intensive coring and sub-bottom profiling would be required to characterize the extent and magnitude of uplift in the disposal pit.

<u>Volumetric Change Analysis</u>

Revisiting the simplified annualized rates of change from survey interval to survey interval presented in Table 2-4, it is possible to develop rough profiles for lagoon sediment volume changes (Figure 2-7). In this figure, it is evident that in the early post-restoration years, surface elevation losses (blue area) vastly exceeded sediment accretion (red area), thus resulting in a cumulative reduction in sediment volume compared to as-built (1996) bathymetric conditions (white bars show cumulative condition in comparison to as-built elevations). This early loss of elevation was likely due to subsidence in the central basin, sediment erosion and export, as well as consolidation of fine sediments in the east basin, and continued through the 2001 lagoon survey. Sometime between 2001 and 2008, the sediment accretion rate overtook the consolidation and erosion rate such that by 2008, the lagoon had accumulated a net of slightly over 140,000 cubic yards of sediment (Table 2-3, Figure 2-7).

However, as described above, when making surface-to-surface comparisons, only net increases or decreases in elevation can be used to quantify volumetric change. With the added information regarding dredge material export and extent of estimated subsidence discussed above, it is possible to further examine sediment budgets within the developing lagoon. In Figure 2-6, the 1996 as-built surface was subtracted from the 2008 surface, and the difference was summed as volumes of surface gain and loss (Table 2-3). Table 2-6 uses additional information on dredge export volume provided by CDFG and rough subsidence estimates to create a better estimate of the breakdown of this volumetric change. As discussed previously, the estimate of subsidence volume is best expressed as a broad range from 130,000 cubic yards to 355,000 cubic yards, a figure subject to future revision as more extensive subsurface data become available using sub-bottom profiling and additional hydroprobing or coring.

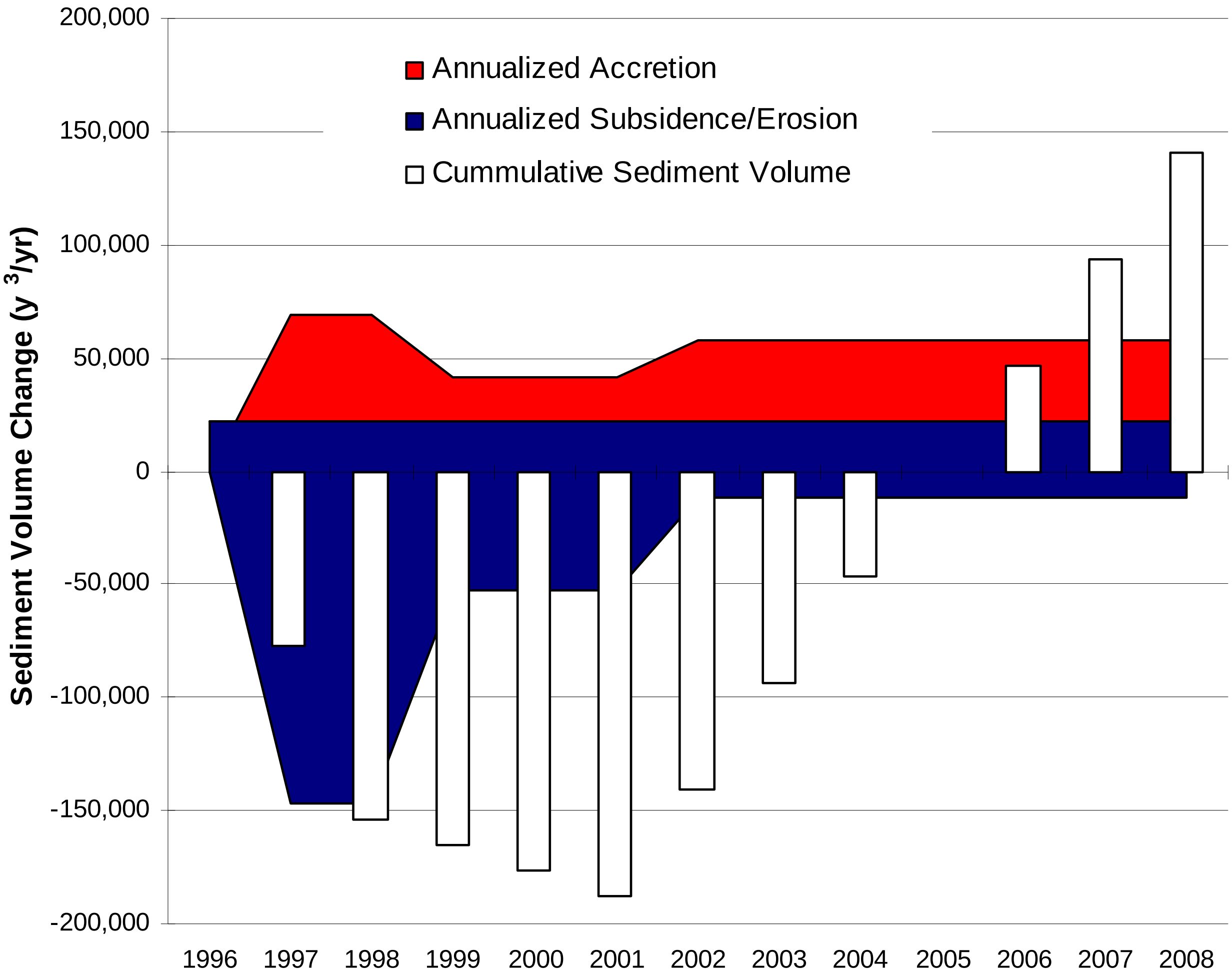


Figure 2-7. Annualized sediment volume gains/losses and cumulative change over time.

Table 2-6 suggests a long-term lagoon-wide accretion rate of approximately 50,000 to 69,000 cubic yards per year when taking into account both accretion above the as-built surface and accretion between the as-built surface and the subsided surface within the central basin disposal pit. This is balanced against erosion, subsidence, and dredging export of sediment totaling approximately 465,000 to 690,000 cubic yards, or an average rate of 38,750 to 57,500 cubic yards per year. This results in a net accumulation of sediment of 140,000 cubic yards (11,700 $yd^{3/}yr$).

Table 2-6. Estimated sediment budget within Batiquitos Lagoon (1996 to 2008).

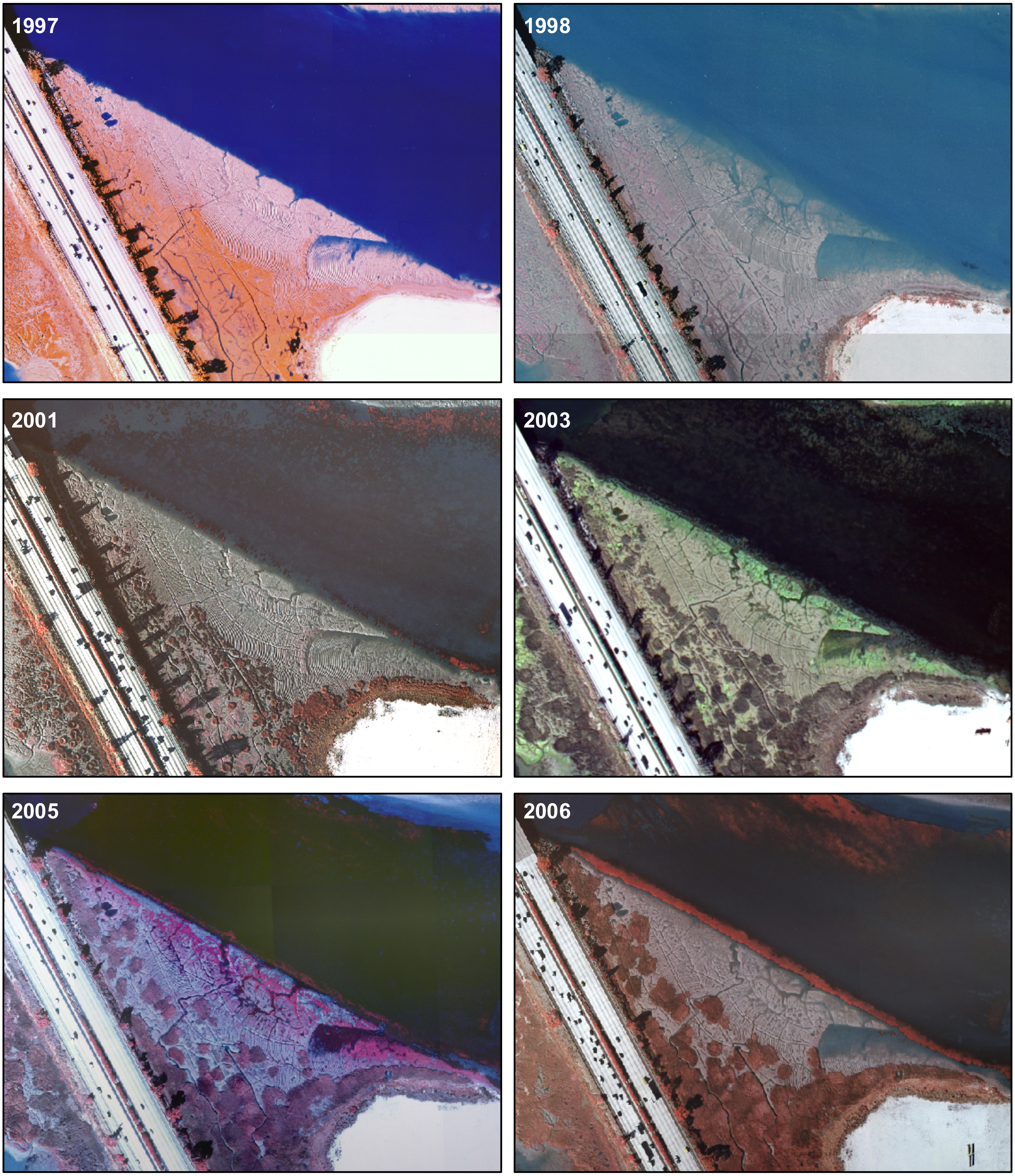
	Volumetric Change (yd3)				
	Accretion	**Erosion**	**Subsidence**	**Dredging Export**	**Net**
West Basin	78,995	(18,641)		(31,026)	29,328
Central Basin	319,729 to 545,027	(33,610)	(130000) to (355,298)	(175,812)	(19,693)
East Basin	206,311	(75,682)			130,629
Total	**605,035 to 830,595**	**(127,933)**	**(130000) to (355,298)**	**(206,838)**	**140,264**
Est. Annual	**50,420 to 69,216**	**(10,661)**	**(10,833) to (29,608)**	**(17,237)**	**11,689**

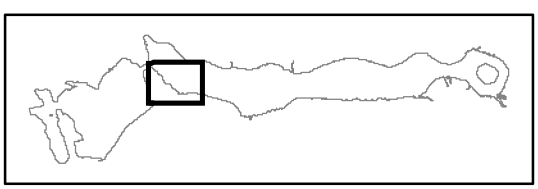
Table 2-3 shows 206,000 cubic yards of accretion occurred in the east basin over the 1996 to 2008 time period, which translates to an annualized rate of slightly over 17,000 cubic yards per year. A similar calculation in the west and central basis results in an estimate of 52,000 cubic yards per year of accretion. It should be noted, however, that there has been a significant change in the rates of sediment erosion and accretion since the early post-restoration period in comparison to later periods. As indicated in Figure 2-7, the rates of sediment gains and losses have significantly changed in the lagoon and have shifted from a system that had a net reduction in sediment volume early in its post-restoration condition to a system that is rapidly accumulating sediment today. By focusing only on the period of time between the 2001 and 2008 surveys when subsidence in the central basin disposal pit would have been at its lowest rate, the estimated influx of sediment from littoral sand sources is estimated at approximately 35,000 cubic yards per year, omitting any residual subsidence of the central basin disposal pit. During this same period, a rapid increase in fluvial source sedimentation in the eastern basin occurred with an annualized rate of infill of 34,000 cubic yards per year. It is believed that much of the fine sediment was introduced to the lagoon during the wet winter of 2005 in a series of episodic loading events, while littoral sand influx has likely occurred at a variable rate in a more persistent pattern.

2.2.3 Hydrogeopmorphic Evolution

In addition to the large-scale processes of sediment influx, consolidation, and tidal current redistribution, more localized changes in the lagoon geomorphology occurred after the reintroduction of tidal circulation. Among these have been shoreline and bedform erosion, loss of land such as the abandoned railroad spur in the west basin, and development and consolidation of tidal channels along mudflats. The high-resolution aerial photographs from 1997, 1998, 2001, 2003, 2005, and 2006 were used to describe and interpret these physical changes by providing a time-series look at fine details of the lagoon development (see Chapter 3, Figure 3-2).

At the time of project completion, the shoreline and lagoon bottom were scarred by concentric ridges and valleys made by the sweep of the dredge cutter-head when making the restoration dredge cuts. Figure 2-8 shows scars on the east side of I-5 on the south side of the east basin. This area occurs within the lee of the I-5 causeway fill and is in an energetically quiescent area of the lagoon. Figure 2-9 details a higher energy portion of the northern shoreline of the east basin approximately half way into the basin. Areas of topographic and hydrographic change at the east end of the basin where San Marcos Creek and Encinitas Creek enter the system are shown in Figure 2-10. The most striking erosion and deposition features were found in the west basin and along the shoreline marsh adjacent to the central basin flood shoal (Figure 2-11). These changes to lagoon hydrogeomorphology will be explored in detail in the Discussion section.





Evolution of east basin dredging scars in quiescent areas

Figure 2-8

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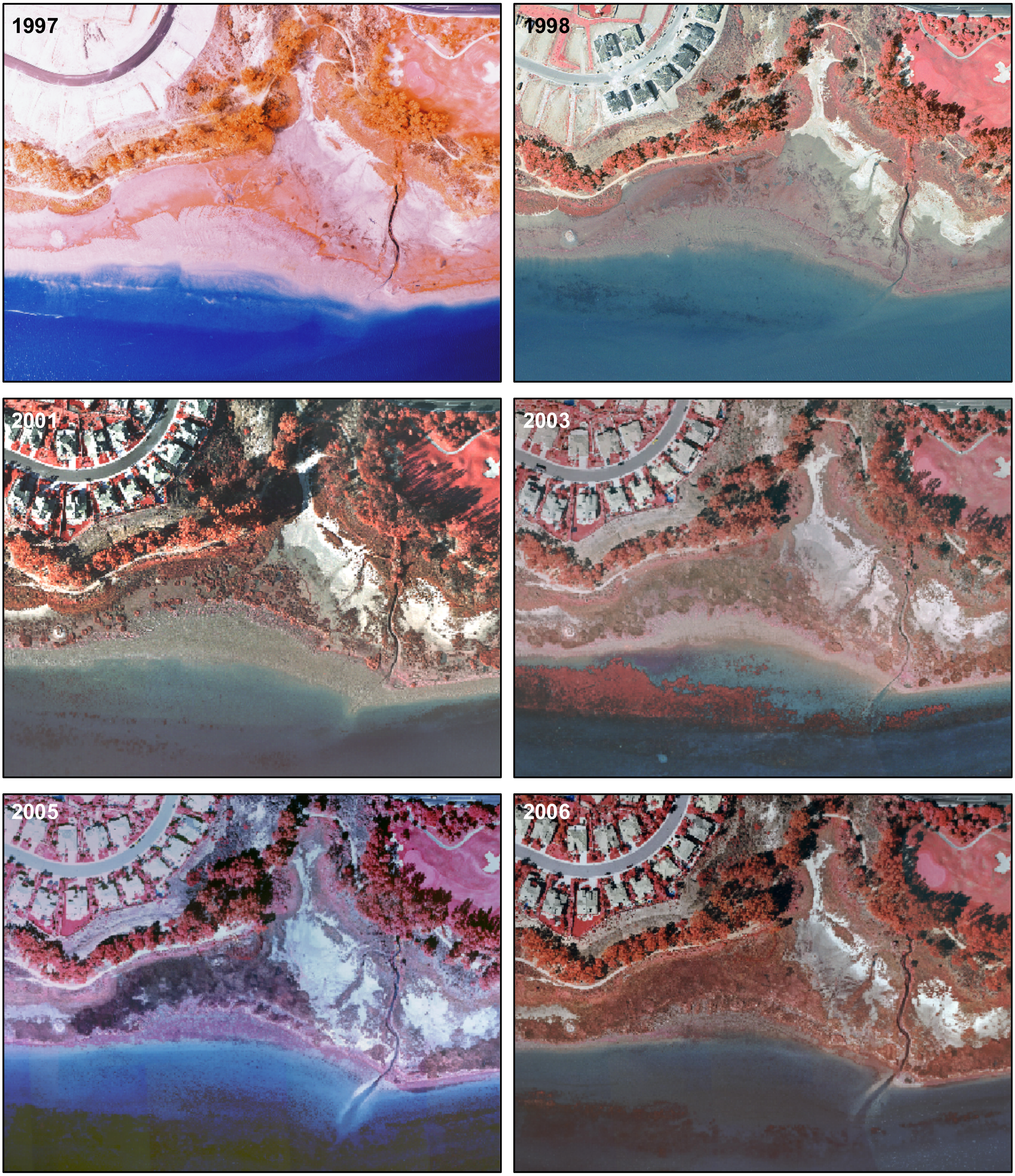

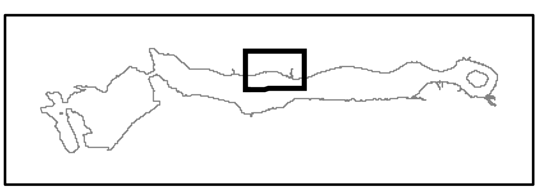

Evolution of east basin dredging scars in exposed areas

Figure 2-9

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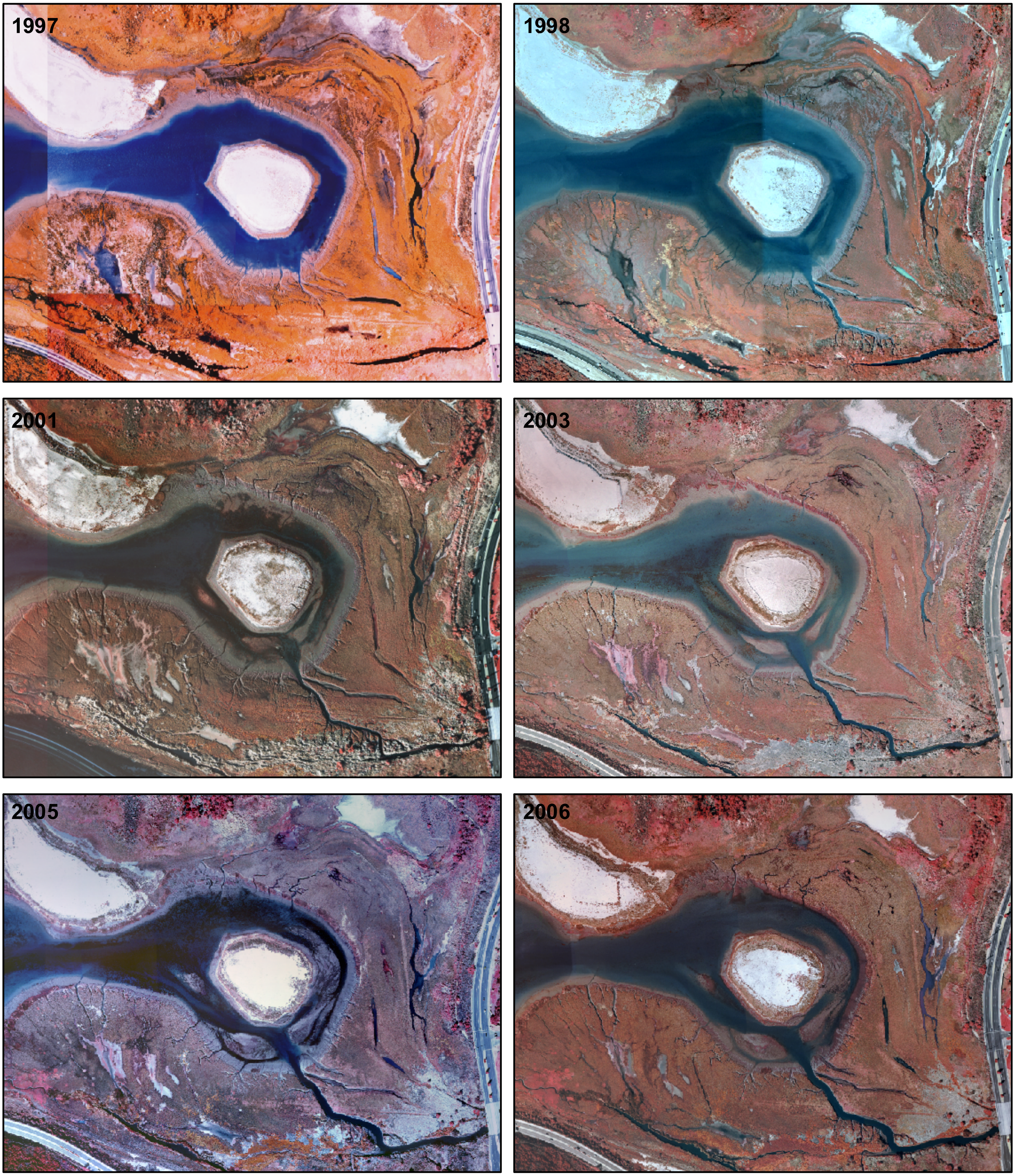

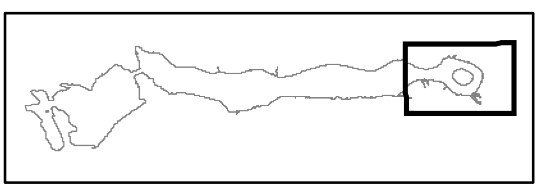

Evolution of channel development at east end of east basin

Figure 2-10

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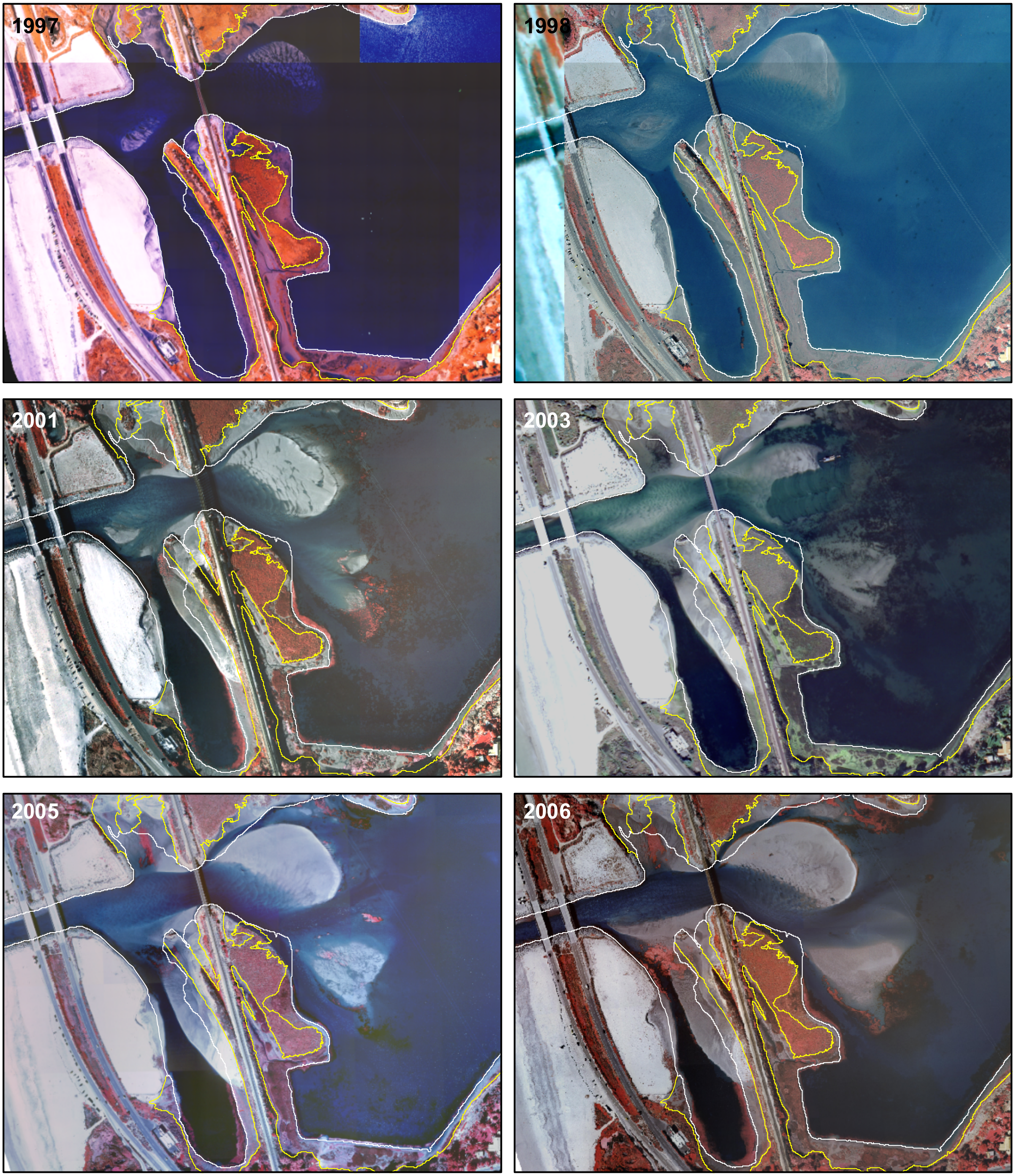

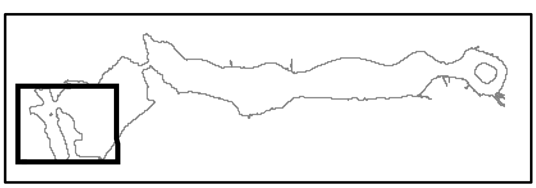

Evolution of west and central basin shoreline erosion and shoal development

Figure 2-11

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2.3 DISCUSSION

2.3.1 Tidal Assessment

There has been a significant loss of tidal drainage between the initial 1997 post-opening conditions and 2008. Along with this loss of tidal drainage, there has also been a significant lag in tidal drain-out of the lagoon and an increased decoupling of the lagoon basins from the ocean and each other. As detailed above, there has also been an approximately 81 minute and 141 minute increase in the maximum tide lag in the west and east basins, respectively. Much of this change in lag time was manifested early in the post-restoration evolution of the physical system. By 1999, the lag in the eastern basin had reached 57% of the total lag observed in 2008. For the west and central basins, the lag achieved in 1999 was 69% and 84%, respectively, of that observed in 2008. The rate of lag increase slowed in more recent years and will vary over time with shoal accumulation and dredging events.

The continued muting of the system and loss of low tide drainage has the effect of narrowing the tidal range in a manner that increases the frequency of inundation throughout all but the extreme high end of the intertidal zone. This change results in a compression of the classical intertidal estuary zonation patterns towards the higher end of the normal intertidal range, such that low marsh vegetation (typically extending to a low elevation near mean sea level) is raised higher on the shoreline and begins to displace middle marsh vegetation occurring within normal elevation ranges. The middle marsh is then pushed upward as well and displaces some of the higher marsh vegetation. The higher marsh remains limited at the upper boundary by its restriction to areas with saline influences that prevent terrestrial vegetation from effectively competing with salt tolerant marsh plants. The effect of this compression of the marsh zones to higher shoreline elevations is the reduction of the total area of marshlands and the creation of a marsh habitat that is then subject to variable inundation frequency levels with maintenance dredging events.

The slowed drain-out at low tides, with a relatively synoptic return of water levels with ocean flood tides, also plays a role in limiting the exposure period for mudflats below the vegetated marsh zones. Under fully tidal conditions, water drops along the wetland shorelines exposing a continually broadening band of mudflat until such time as the tide turns and the mudflat gradually narrows as it is inundated again. With tidal muting, less mudflat is exposed overall and the duration of mudflat exposure is reduced. As a result, there is less temporal and spatial availability of mudflat for species dependent on exposed mudflats, such as foraging shorebirds. In Batiquitos Lagoon, the recent sedimentation in the east basin has served to counteract the spatial loss of mudflat by lifting the floor of the lagoon at the east end to elevations that have sustained mudflats even at higher perched water levels.

2.3.2 Bathymetric Assessment

As predicted, flood shoal formation commenced during 1997, and littoral sand shoals grew rapidly following mouth opening. This was the result of beach sand entrainment in the lagoon rather than erosion scour and re-deposition of materials from within the system (M&N 1997b). By the third quarter of 1997, both flood shoals in the western and central basins had become intertidal. No bathymetric surveys were conducted during 1997, so it was not possible to determine the actual volume of these shoals or the rate of sediment accretion during this period of lagoon equilibration. However, estimates made using rough calculations suggest this shoal complex likely exceeded 30,000 cubic yards by the end of the third quarter of 1997 (40,000 yd^{3}/yr) (M&A 1998). In 2003, using the bathymetric surveys completed in 1999 and 2001, the flood bar shoaling rate was estimated at 22,500 (1996 to 1999) and 28,000 (1996 to 2001) cubic yards per year (M&N 2003). However, these early estimates of influx rates were based on rough spatial analysis of aerial photographs (M&A 1998) and surface to as-built comparisons (M&N 2003). Neither survey included such factors as fine sediment export or subsidence beneath the building flood shoal, due to lack of data on these elements.

Shoaling rates in the lagoon remain a matter of considerable speculation due to a paucity of physical data through time. However, present estimates of littoral sand capture rates over the entire post-restoration lagoon history range from 33,000 to 52,000 cubic yards per year, depending upon assumptions regarding the central basin disposal pit subsidence. Most recently, from 2001 to 2008, it is estimated that littoral sand has been deposited into the lagoon at an annualized rate of roughly 35,000 cubic yards per year. Coincident with sand influx, dredging throughout the post-restoration lagoon history has extracted sand at an annualized rate of only 17,000 cubic yards per year, half the rate of low estimates of infill. Assuming the presently estimated shoaling rate has been maintained through time, this would suggest an accumulation of sand occurring at a rate of 18,000 cubic yards per year, or approximately 216,000 cubic yards since lagoon opening. However, it should be noted that given uncertainties regarding subsidence within the central basin disposal pit, the volume of accumulated sand might range between 192,000 and 420,000 cubic yards. It is believed that this magnitude of accumulation has not been detected because of the counteractive effect of subsidence of the disposal pit under the growing flood shoal of the central basin.

Prior maintenance dredging events conducted by CDFG at Batiquitos Lagoon have generally aimed to dredge the flood shoals down to an as-built elevation of –1.92 feet MLLW (–4.56 feet NGVD) (T. Dillingham, pers. comm.). However, the accumulation of sediments in the central basin below the initial as-built surface has significant ramifications to future dredging needs. In effect, the system has been subject to considerable deferred maintenance that has not affected the overall functioning of the lagoon to the extent that it could in the future. As the central basin disposal pit has achieved greatly reduced consolidation rates, based on survey-to-survey comparisons, the volume of shoal sand that has been accreting on the subsiding basin floor has now begun to be manifested as elevated shoal development. As a result, the net accretion above removal volumes has become a major concern to maintaining the health of the lagoon.

In addition to littoral sand capture, the accumulation of fluvial sediment within the lagoon is a concern to maintaining lagoon health. While the present analysis only addresses a few points in time, it clearly indicates fluvial source sediment accumulation within the east basin has increased in recent years. Early in the lagoon's post-restoration history, a net loss of sediment occurred in the east basin, while substantial sediment accretion has occurred in the more recent period. This sediment load is dominated by fine fraction sediments rather than sand. Table 2-6 quantifies the as-built (1996) to 2008 accumulation at approximately 206,000 cubic yards with a balancing erosion of 76,000 cubic yards. The result of this deposition is reduced water depth as well as creation of land bridges to the E-3 nesting site. Figure 2-4 clearly exhibits loss of open water depth and area over time.

There have been several episodic events during the past 12 years that likely contributed to sediment loading of the east basin. The first was the restoration of tidal influence to Batiquitos Lagoon, which resulted in the development of extreme drainage gradients at the outflow delta of San Marcos Creek. During 1997, scouring by the San Marcos Creek outflow began to form a new channel across the sediment fan where it joins the lagoon. In 1998, this channel was further eroded by fluvial storm flow discharges. A second major event was the heavy rainfall during the 1997-1998 El Niño. The season resulted in a rainfall yield with a regional probabilistic recurrence frequency of once every 17.4 years and ranked as the ninth wettest year in the 158-year regional rainfall history that was reviewed (San Diego Weather Forecast Office). Exacerbating the high seasonal rainfall during 1998 was the fact that the rainfall accumulation pattern was made up of a number of very large, late season storms that led to heavy flooding and high sediment and debris flows being generated from local watersheds. A third large potential contributor of sediment into the lagoon was the record rainfall in the 2004-2005 winter season which likely accounted for the bulk of the sedimentation observed in the east basin post 2001. The 2004-2005 water-year was the third wettest year in the regional rainfall history. At 22.49 inches, the year was only 3.48 inches behind the highest rainfall season of 1883-1884.

Not clear from the single numeric comparison between 1996 and 2008 is the ability of the lagoon to shed some fine sediment loads. Based on the interim bathymetric surveys conducted in 1999 and 2001, it appeared that fine sediment and debris that was likely deposited during the El Niño flooding of 1997-1998 may have been substantially purged or consolidated by 1999 (Figure 2-6). Between 2001 and 2008, no bathymetric surveys were conducted within the east basin. The substantial sediment load that occurred between the two surveys was likely deposited principally during the 2004-2005 winter storms. The reduced tidal prism associated with the buildup of the flood shoal may have contributed to the greater capture of fine sediments. It also appears that the same degree of sediment flushing that may have occurred early in the lagoon’s history did not occur in later years. Some storm deposited materials may be eventually flushed from the system; however, the prolonged residence of sediment results in increased consolidation and cohesiveness that resists subsequent suspension and transport out of the system. As a result, while limited erosion of the fine sediments in the east basin are anticipated in the future, it is unlikely that substantial export will occur without a rehabilitation dredging event to remove fine sediments from the east basin.

Although the influx of new sediment into the east basin could be calculated at an annualized rate of approximately 11,000 cubic yards per year, it is more likely that the sedimentation resulted from a series of punctuated episodic events rather than chronic infill. The restoration of tidal influence within the lagoon was a one-time event, and the two major El Niño events that occurred since lagoon opening individually have probabilistic return frequencies that are in excess of the length of time that has passed since restoration. Non-point source sediment discharge within the watershed has become more stringently regulated since the initial restoration of the lagoon. Given the episodic nature of fluvial sediment loading, it is not known whether sediment loading rates observed in the first years post-restoration will continue, decline, or increase in the future.

2.3.3 Interaction of Tidal Muting and Bathymetric Change

Tidal Prism

Tidal prism is defined as the volume of water contained between the high and low levels within a basin defined by the lagoon bathymetry. In this case, it is the amount of water that is exchanged between the ocean and lagoon during a tidal cycle. The greater the tidal prism, the greater degree of flushing the lagoon receives and the lower the risk of lagoon mouth closure due to build up of sand across the entrance of the lagoon. Greater tidal prism does not translate into lower levels of flood shoal accumulation. Early calculations used “potential” perigean spring tidal prisms with a tide range from –1.6 feet MLLW to +7.4 feet MLLW for multiple years between 1887 and 1978 to support lagoon restoration design alternatives analysis with respect to mouth closure and sediment accumulation (Jenkins et al. 1985). Table 2-7 summarizes these historic potential perigean spring tidal prisms for the lagoon used by Jenkins et al. with the pre-construction (1994), as-built (1996), and 2008 evolved conditions added, also applying potential perigean tidal prism range.

Table 2-7. Historic tidal prism conditions within Batiquitos Lagoon.

Year	Potential Perigean Tidal Prism (million yd^3)	Percent of 1887 Tidal Prism
1887	5.65	100%
1888	4.85	86%
1960	4.30	76%
1965	3.62	64%
1978	0.01	0%
1994	0.00	0%
1996	3.39	60%
2008	3.32	57%

The difference between the potential perigean tidal prism from 1996 and 2008 is a result of sediment accumulation within the lagoon. The true prism is limited to the range of fill and drainage that can occur given tidal muting and lag influences. There have been significant technical debates over what tidal prism range is most meaningful relative to lagoon closures or system flushing. For Batiquitos Lagoon, the tidal prism has been quantified as both the mean diurnal tidal prism (MHHW to MLLW) as well as the mean tidal prism (MHW to MLW). The restoration objectives from the Final EIR/EIS (Volume 3) identified the mean diurnal tidal prism goals for Mitigated Alternative B to be 60 million cubic yards (City of Carlsbad and U.S. Army Corps of Engineers 1990). This translates to 2.2 million cubic yards of prism between MHHW and MLLW. Under current conditions, the mean diurnal tidal prism of the lagoon is 1.94 million cubic yards. Lagoon closure criteria were discussed at some length within Appendix H4 Tidal Inlet Design Issues of the Final EIR/EIS. For the oceanic wave environment existing in the Batiquitos Lagoon region, it was determined that the mean tidal prism (MHW to MLW) necessary to maintain an open inlet was 0.61 million cubic yards. However, given the degree of uncertainty, a factor of safety of 2 was required to provide the minimum acceptable tidal prism to avoid mouth closure. This translates into the assumption that when Batiquitos Lagoon has a mean tidal prism (MHW to MLW) of less than 1.22 million cubic yards, it is at a higher risk of closure than when the prism is maintained at a higher volume. In 2008, the mean tidal prism (MHW to MLW) for the lagoon was calculated to be 1.36 million cubic yards, thus maintaining an acceptable inlet closure factor of safety of 2.23.

While the tidal prism volume suggests that the lagoon is not at risk of closure, Appendix H4 of the Final EIR/EIS (City of Carlsbad and U.S. Army Corps of Engineers 1990) cautions that this simplified view of closure risk fails to consider many other factors; and notwithstanding the tidal prism within the lagoon, caution must be applied when considering small tidal prisms such as that found at Batiquitos Lagoon. It is appropriate to consider not only prism volume but also such factors such as available littoral sand supply, presence of significant cobble, and the accumulated flood shoal volume. Inlet closure risk can be heightened or reduced based on availability of sand resources within either the littoral cell or the flood shoal. The accumulation of cobble in the inlet exacerbates risk because of the greater energy required to displace cobble from an inlet bar.

In the case of Batiquitos Lagoon, several conditions exist that may increase the risk of mouth closure. First, there is the large accumulation of sand within the west and central basin flood shoals that is building at an accelerated rate due to the slowing of disposal pit subsidence and lack of adequate maintenance removals (Figure 2-12, Table 2-4). This large accumulation of sand has created relatively circuitous flow patterns in the low flood and ebb tide conditions and provides considerable source sand for potential closure events. Second, the west basin is known to support a fairly substantial amount of cobble that may add to the potential for accumulation of a stable inlet bar. Third, tidal flow constrictions at the I-5 bridge and railroad trestle extend the hydrograph for the lagoon, thus lowering the velocity generated in flooding and ebbing tides. Finally, shoaling within the west basin has nearly closed off the southern arm of the west basin (Figure 2-12). The prism within the west basin contributes only 6% to that of the overall lagoon; however, much of this increment of prism could be easily lost due to a single storm event. Two factors counteracting the conditions favoring mouth closure are maintenance dredging that has been conducted to remove shoal impediments and the fact that Ponto Beach does not approach the ends of the entrance channel jetties.

There remains a lack of physical data to truly analyze the condition of the inlet relative to closure risk. Most specifically, there is a critical data gap relative to measurement of current velocities within the inlet to evaluate the scour potential to maintain an open mouth. Given the diminishing prism and the paucity of physical data, it is prudent to diligently monitor lagoon mouth conditions (as called for in the Draft Land Management Plan for Batiquitos Lagoon Ecological Reserve, CDFG 1997) and to be prepared to conduct an emergency opening if necessary. To minimize the closure risk, the lagoon's sediment loading capacity should be restored through a significant rehabilitation dredging. Cobble accumulations in the west basin should be removed from effective flow areas, and deeper maintenance basins should be dredged within the west basin and central basins. Careful consideration should be given to local beach replenishment activities as they pertain to both flood shoal growth rates and potential inlet closure risks. Where increased sediment loading would result from beach nourishment, it should be quantified and mitigated by equally increasing the extent of flood shoal removal. Finally, because the restriction in the aperture of the I-5 and railroad bridge plays a role in limiting the lowest tides,

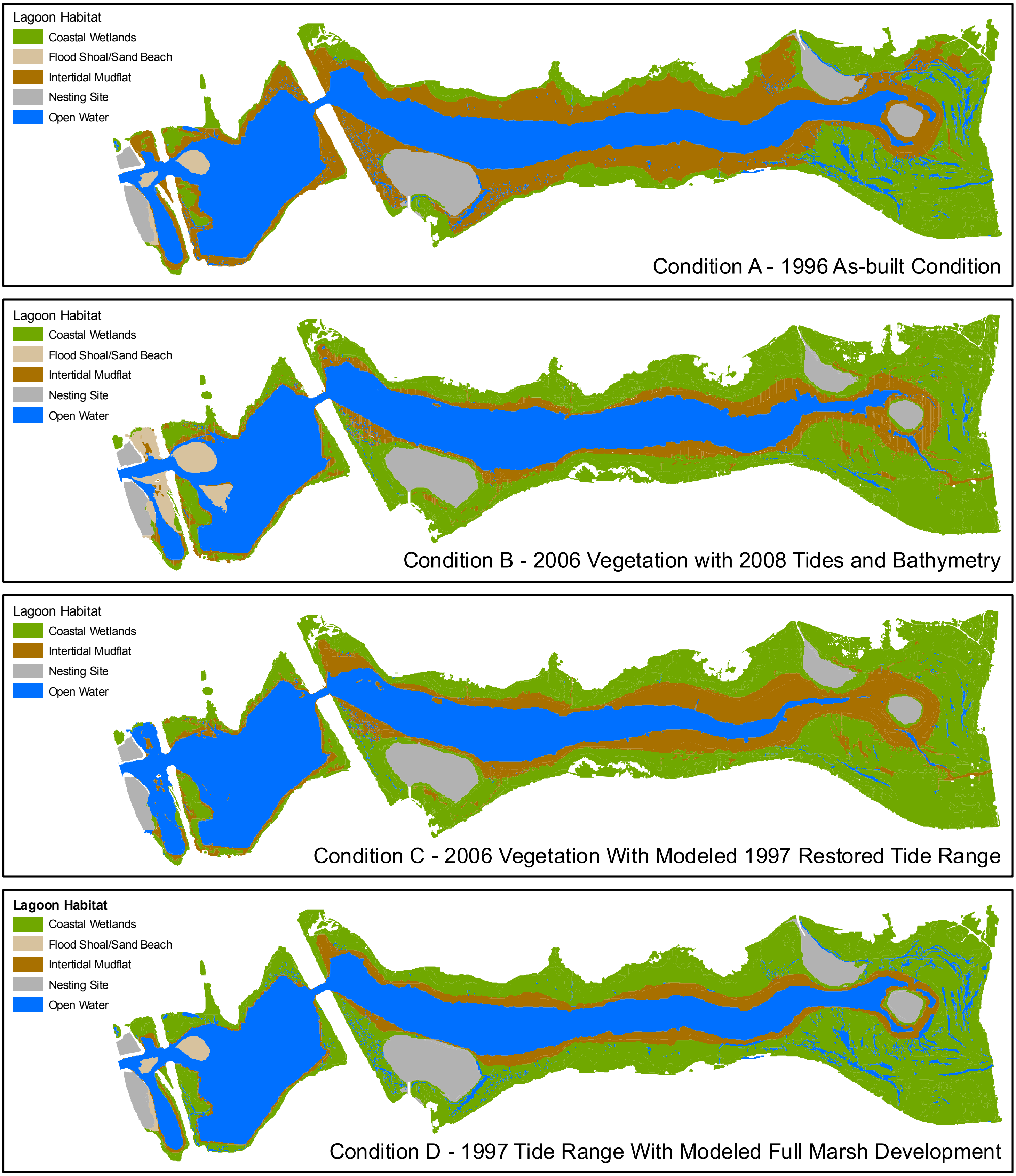
Figure 2-12. West basin and central basin flood shoal conditions (2008)

widening or deepening the bridge apertures would benefit the inlet. Consideration should be given to implementing such measures in association with the I-5 widening project presently under development by Caltrans, and/or the LOSSAN double-tracking project.

Habitat Development

Tidal muting, changes in lagoon bathymetry, and the lack of regular maintenance dredging create positive feedback loops that tend to favor increased sediment trapping and even greater muting over time. This feedback loop is important to consider when making predictions about the future of the lagoon. As tidal range is reduced due to muting, there is less overall water exchange with the ocean. As a result, velocities of tidal flow are reduced and sediment export from the lagoon is reduced. With a greater degree of sediment remaining within the system, the sediment floor rises and develops a flattened bedform. This flattening of the lagoon bathymetry creates conditions that can alter the mudflat exposure and inundation such that large areas of mudflat will be exposed at nearly the same time (rather than gradually) and will be inundated rapidly with the rising tide. The resultant effect of such changes would be a reduction in open water and temporally abbreviated foraging windows for shorebirds.

One very notable and interesting interaction of tidal muting, wetland vegetation development, and bathymetric change is the lagoon habitat blend of salt marsh, mudflat, and open water. When the lagoon was initially opened, the as-built tide range, past inundation history, and bathymetry created 173.7 acres of mudflat based on a lower exposure limit set at the 0 feet MLLW elevation (Figure 2-13, Condition A). By 2006, the infill of vegetation across the higher mudflats combined with tidal muting and changes in bathymetry had resulted in a 47% reduction of the initial mudflat area to approximately 82.0 acres (using 2008 tide and bathymetry data) (Figure 2-13, Condition B). If the tidal range within the lagoon were to be restored to that which



Lagoon habitat distribution under various conditions

Figure 2-13

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existed following restoration in 1997, without conducting any sediment removal within the east basin, mudflats would be anticipated to extend over 115.8 acres of the lagoon, with a loss of open subtidal waters. The increased low tide drainage resulting from the reduction of tidal muting would expose the accreted sediments in the back of the eastern basin as mudflats (Figure 2-13, Condition C).

The dramatic changes in habitat composition between initial post-restoration conditions and those that have evolved (Condition B), or which might be expected with tidal range restoration (Condition C), may initially appear alarming. However, it is appropriate to put the observed evolution of habitats into context with what would be anticipated in a physically static system. If the system were to have experienced no tidal muting and no bathymetric change from as-built conditions, the normal development of vegetation would have resulted in considerable conversion of mudflat to marsh. By modeling marsh vegetation expansion across the available elevation range using tidal inundation frequency as a controlling factor for vegetation growth, it was predicted that mudflats would be reduced to 61.4 acres, or 35% of the mudflat existing at the time of lagoon opening (Figure 2-13, Condition D). This predicted mudflat area is similar to the condition presently existing. Further, the extent of salt marsh is what would be anticipated given the developed tidal conditions and introduction of the low marsh dominant Pacific cordgrass (*Spartina foliosa*) to the system (see Chapter 4). Based on the comparison of predicted habitat development with that observed in the lagoon, it has been determined that the broad scale balance of marsh, mudflat, and open water habitat development is tracking well with initial expectations for the lagoon. More detailed habitat analysis is examined in Chapter 3.

While the habitat element that has been most reduced as a result of the evolution of the lagoon has been mudflat, this replacement by marsh vegetation was fully anticipated as a part of normal system evolution in the Draft Land Management Plan (CDFG 1997). The difference between predicted mudflat under static physical conditions and that actually observed is principally a product of sediment loading to the east basin and rising bathymetry in this larger basin, in counteraction to a loss of tidal drainage and thus rising low-tide elevations. The broad system changes illustrated in Figure 2-13 are based on a combination of tidally-derived elevation breaks and highly simplified habitat mapping (see Chapter 3 for more detailed habitat mapping). The importance of the habitat balance exhibited in Figure 2-13 is that the spatial distribution of habitats comprised of wetlands, open water, mudflat, and nesting sites remains relatively consistent with what would have developed under the original design conditions, although the numeric ratios of habitat composition fluctuate depending upon tidal muting and sediment loading. The balance of habitats at any given time may vary from that initially targeted. However, each primary constituent holds distinct, yet contributory, ecological values. For this reason, it is less important from a system evolution standpoint to maintain a particular mix of habitat than it is to ensure that the overall lagoon functions as an ecosystem unit.

2.3.4 Hydrogeomorphic Evolution

Notwithstanding the larger processes and evolution of tidal exchange and lagoon-wide sediment budgets, smaller scale evolution of the lagoon has been occurring in parallel. These hydrogeomorphic processes are important in defining tidal water drainage patterns across exposed flats, developing sediment physical and chemical characteristics, and ultimately the development of biological communities within the system.

Tidal inundation frequency and regularity plays a controlling role on the development of sediment chemistry including salinity, oxidation-reduction potential (ORP), and pH. Tidal drainage and fill exposes sediments to intermittent oxygenation and surface water evaporation. The effectiveness of tidal controls on sediment chemistry is mediated by the physical properties of the sediment, as well as efficiency of sediment drainage during low tide exposure windows. As a result, it is worthwhile to examine how the small-scale evolution of tidal flat drainages and sediment development has occurred through the post-restoration evolutionary history of the lagoon. From this review of the physical nature of the site, it is believed that biological features of the lagoon may be better understood and explained and benefit the planning and implementation of future restoration projects.

At the time of project completion, the shoreline and lagoon bottom were scarred by concentric ridges and valleys made by the sweep of the dredge cutter-head. Figure 2-8 shows these scars on the east side of I-5 on the south shore of the east basin. From these photographs it can be seen that only limited weathering of the topography occurred, and the scarring remained apparent 10 years after lagoon opening. This area occurs within the lee of the I-5 fill and is thus not exposed to significant wind wave environments. Figure 2-9 details a higher energy portion of the northern shoreline of the east basin approximately half way into the basin. In this series of photographs, the cutter-head scarring is evident early in the post-restoration history (1997-2001). By 2003, however, little surficial evidence of the scars remained.

The degree to which the scars became less evident in various shoreline and subtidal locations is a function of several factors. First, the predominant wave direction is from the west. As a result, the shoreline in the lee of I-5 rarely receives much wave energy, while the shoreline approximately half way down the axis of the east basin is subject to fairly regular wind waves during the mid-day onshore winds. These wind waves eroded the stiff clay ridges of the scars. Second, the eastern end of the lagoon has higher ambient suspended sediment loads than the relatively clear western end of the lagoon. This is the result of fine sediment inputs from fluvial sources, high sediment resuspension by wind waves, and low flushing of sediments in the eastern end of the basin than the west. These fine silts and clays dropped from suspension into the troughs of the scars, leveling them out in a visual sense. However, fundamental differences in sediment character remained between consolidated ridges and unconsolidated sediments found within the troughs.

Review of the aerial imagery suggested that the sediment differences from ridge to valley in the dredge scars influenced tidal channel and vegetation development patterns. The stiff clay ridges and soft unconsolidated troughs affected the development of drainage patterns by forming less erosive dikes along the edges of highly erosive cuts. Where the dredge cuts were oriented perpendicular to the shoreline, the pattern favored maintenance of simple drainage patterns with narrow and small watersheds consisting of single dredge sweep scars. Where dredging sweeps were oriented parallel to the shoreline, development of more complex drainage channels occurred. Convoluted patterns of pooled water in troughs gradually began to be connected by breaks that formed complex micro-drainage basins on the flats. The higher ridges drained more quickly than the troughs, likely creating higher ORP along the ridges and therefore more rapid vegetation establishment. The vegetation would subsequently influence drainage patterns by increasing elevation, sediment trapping, and resistance to erosion where the vegetation occurred.

As a result, feedback loops began to develop where physical drainage patterns influenced vegetation patterns and vegetation patterns influenced drainage patterns. The growth and expansion of cordgrass ultimately crossed high ridges and lower channels of the dredge cuts. In some places, the increased blockage of poorly defined channels caused ebbing or rising tides to jump channel banks and eventually cut new channel alignments diverting and connecting adjacent watersheds.

As more evidence is being developed on a regular basis that suggests that increased channel complexity is a positive characteristic for higher marsh function, future marsh creation efforts should consider the effects of microtopographic relief that results from some dredging techniques. Dredge sweeps aligned perpendicular to the shoreline tend to develop such limited drainage basins as to not develop more complex drainage basin geometries. As a result, the rate of development of natural marsh and mudflat drainage patterns may be significantly slowed and ultimately dependent upon biological factors such as vegetation development and benthic organisms and demersal fish activities to generate conditions favoring complex drainage development.

The feedback loops between physical and biological development could be seen in other areas within the lagoon as well. At the far eastern end of the east basin, dense marsh vegetation across very low gradient slopes fostered the development of highly dendritic tidal channels (Figure 2-10). Conversely, the large inflows from San Marcos Creek cut a relatively direct course through the same marsh plain to the open lagoon waters. Long-term persistence of tidal ponds and depressed salt panne habitat is readily apparent in the photographic series. This persistence of these features is a function of low sedimentation rates at higher tidal levels, combined with low sediment ORP and high sediment salinity that has thus far precluded the establishment of marsh vegetation. Where salt pannes and tidal ponds exist at the east end of the lagoon, it is anticipated that over time channels will eventually develop to connect these features to the larger tidal basin. Once this occurs, rapid development of the marsh habitat will occur as sediment chemistry is modified to conditions more conducive to supporting vegetated habitats.

The uneven bottom resulting from the dredge sweeps not only had physical and biological consequences; it also affected the biological monitoring sampling efficiencies and variability between samples. The alternating stiff clay ridges and fluid, silty troughs complicated shoreline fish sampling efforts by interrupting the connection of the nets with the bottom, as well as making it difficult for the sampling staff to walk the nets to shore. In addition, variations in benthic invertebrates collected from either ridges or troughs likely led to some of the high variability observed within stations and sampling years (see Chapter 8). The differential invertebrate distribution and the highly variable terrain also likely affected the foraging activities of birds documented in Chapter 6.

Early observations of the dredge scars resulted in some concern as to how the system would respond to these anthropogenic artifacts. The monitoring imagery demonstrates that the lagoon ultimately did respond with a gradual resculpting of the scar features. In low sediment load quiescent waters (Figure 2-8), it can be anticipated that visual evidence of the lagoon's restoration origins will potentially persist for decades into the future. The biological and physical functioning of these scarred intertidal areas, however, appears to be developing irrespective of the artificial appearance.

The loss of shoreline and erosion of higher bluff areas in the west basin and along the shoreline marsh adjacent to the central basin flood shoal occurred fairly shortly after lagoon opening (Figure 2-11). In the west basin, the principal loss of shoreline features occurred on an abandoned railroad spur that was damaged by heavy surf propagating into the lagoon mouth. The geometry of the lagoon mouth and the building flood shoal in the west basin resulted in wave refraction to the south of the designed channel, with waves impacting the steep slopes of the railroad spur embankment. This resulted in both the collapse of this embankment as well as wave reflection to the opposing shoreline where significant erosion of the W-2 nesting site occurred. Even prior to reflective wave erosion of the W-2 nesting site, non-breaking oceanic swells within the west basin generated enough bed-shear stress to drag the steep foreshore slope out to more stable beach-like profiles. This resulted in nesting site erosion and deposition of sands lower on the beach profile. These processes are part of the natural equilibration of the site post-construction; however they have resulted in an unanticipated and undesirable erosion scarp development along the nesting site in a manner that limits site use by western snowy plovers (*Charadrius alexandrinus nivosus*), a species that was to be benefited by the beach interface.

Waves also played a role in distributing shoal sands within the west basin. This can be seen in the northern cove of the basin east of the W-1 nesting site. In this area, sands were pushed up into the cove while marsh muds were eroded away. This transition can also be seen in habitat and vegetation mapping, where the site converted from salt marsh and mudflat to sand by year 3 (1999) (see Chapter 3). Shoal sands were also moved onto the east shoreline of the basin, constricting the opening to the southern part of the basin. In Figure 2-11, the accreting sand burial of eelgrass (*Zostera marina)* transplants in the 1998 image (dark lines in the waters adjacent to the eastern shoreline) can be seen in the 2001 image.

While ocean swell and wave-driven erosion and deposition patterns were most common in the west basin, flow-mediated shoreline erosion was most notable within the central basin, particularly just east of the railroad trestle constriction (Figure 2-11). In this area, mid-channel deposition of shoal sands constrained the tidal flows and forced migration of the channel to both the north and south of the shoal at various periods in time. The redirected channels undermined the soft marshland sediments immediately west of the shoal causing mass-wasting erosion of the bank. The most extensive erosion was seen on the southern side of the channel where coastal salt marsh was undercut by deep channel incision and lateral migration, resulting in the collapse of the salt marsh into the channel. While the majority of marsh loss occurred prior to 2001, progressive incremental losses of marsh plain from the central basin continued intermittently throughout the 10-year monitoring period, depending upon the status of the flood shoal and maintenance dredging activities.

2.4 RECOMMENDATIONS

In order to maintain the lagoon in a physically and biologically healthy state, the following maintenance recommendations should be considered for implementation.

- Update and finalize the Draft Land Management Plan for Batiquitos Lagoon Ecological Reserve (CDFG 1997), adding a section on adaptive measures to respond to sea-level rise.

- Implement the Land Management Plan for Batiquitos Lagoon Ecological Reserve.

- Review and update the Land Management Plan every two years to determine if it is providing consistency with project goals.

- Provide an adequate, dedicated, and accessible management and maintenance budget.

- Appoint a Steering Committee to provide regular technical and fiducial oversight, as well as regular evaluation of the Land Management Plan and its implementation.

- Perform periodic system-wide bathymetric surveys (approximately every three to five years) to monitor bathymetric trends beyond the scope of biennial maintenance dredging and to improve shoaling rate estimates.

- Conduct a comprehensive sub-bottom profiling and deep profile coring of the disposal pit and sand shoal to identify the extent of sediment that has accreted over the sand cap and the elevation of the top of the cap and underlying cap-mud interface.

- Complete a rehabilitation dredging event to remove the estimated 216,000 cubic yards of sand that has been deposited and not removed by maintenance dredging, creating a pit to increase the capacity of the lagoon to receive incoming littoral sands in the future.

- Excavate deep sediment traps within the central basin shoal area to collect and remove shoal sands below the sill elevation of the railroad trestle to reduce flow impediments and prolong time between maintenance events.

- Excavate cobble from the west basin and remove materials to areas outside of active shoal environments. Excavate a shallow basin in the west basin to trap cobble from the beach.

- Reuse cobble to stabilize beach profiles at the W-2 nesting site, and to protect eroding banks within the west basin.

- Conduct regular maintenance dredging, targeting the estimated 33,000 to 52,000 cubic yards of sand believed to be deposited annually. This would increase the dredging target volume to 66,000 to 104,000 cubic yards every two years or 99,000 to 156,000 cubic yards every three years.

- Consider implementing a strategic dredging within the east basin to remove sediment from areas beneficial to physical and biological function. This includes potential removal of shallows near I-5 to reduce basin muting and dredging around the E-3 nesting site to restore its isolation from ground predators.

- Consider an expansion of mudflats and marshlands within the southern portion of the central basin as a beneficial re-use of dredged east basin fine sediments as an alternative to deep ocean disposal.

- Develop programmatic permits for multiple maintenance cycles and open the annual dredging time window to allow for more economical dredging events.

- Consider a regionally-coordinated maintenance dredging project approach to reduce maintenance costs.

- Implement a current measurement program to determine the velocities and self-scouring potential for the west and central basins in order to evaluate the potential closure risk for the lagoon.

- Identify a contractor to perform an emergency lagoon mouth opening if required. Initiate any required contractual arrangements required and establish a protocol for the opening (*i.e.*, how much material to remove, to what elevation, and where to put the spoils.)

- Perform tidal measurements in each basin every three to five years to evaluate any potential changes in muting and tidal prism, and support the development of dredge goals.

- Create a large-scale hydrodynamic numerical model of the lagoon system and update it every three to five years with the current, tide level, and bathymetric physical modeling results. Use the hydrodynamic model, physical monitoring, and biological monitoring results to evaluate the performance of the lagoon system and determine maintenance dredging triggers, volumes, and locations.

- Collect aerial photographic imagery every three to five years to document changes in habitat conditions and physical features over time.

- Initiate a program to monitor sediment inputs into the lagoon to better understand the source, rate, and periodicity of inland-source sediment loading.

- Investigate alternative dredging and/or sand bypassing options.

- Investigate the possibility of an I-5 bridge replacement or aperture expansion as a part of any future freeway expansion work to improve hydraulics and reduce dredging maintenance needs.

- Investigate the possibility of a railroad bridge replacement or aperture expansion as a part of the LOSSAN double-tracking project to improve hydraulics and reduce dredging maintenance needs.

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